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METAMORPHISM

A STUDY OF THE TRANSFORMATIONS OF ROCK-MASSSES

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PREFACE TO THE FIRST EDITION

THE following pages reproduce in substance a course of lectures delivered at Cambridge. The lack of any published work planned on similar lines has encouraged me to offer them to a wider circle of students.

Metamorphism is here conceived, not as a status, but as a process, viz. a progressive change in response to changing conditions of temperature and stress. In the first part of the book high temperature alone is the ruling condition. This is the case of 'contact metamorphism', which has usually been treated as an isolated phenomenon. Here, on the contrary, a study of purely thermal metamorphism is regarded as the natural line of approach to the more complex problem in which the dynamic factor enters in conjunction with the thermal. This general case (regional metamorphism) is the main subject of Part II. In discussing it I have given special prominence to the controlling influence of shearing stress, as distinguished from uniform pressure, which also has its part. Another factor to which I attach a certain importance is the mechanical generation of heat by the crushing of rocks. In the final chapter the various retrograde changes which may partly undo the work of metamorphism are only briefly noticed.

The subject being metamorphism, not metamorphosed rocks, detailed petrographical description has been reduced to a minimum, but its place is partly supplied by a large number of figures drawn from the microscope. Considerations of space forbid the insertion of chemical analyses: a useful collection of these is contained in a recent publication of the Geological Survey.

In choosing examples mainly from British sources, I am far from undervaluing the work of the many distinguished Continental petrologists who have contributed to our knowledge of metamorphism. Rather has it been my design to show that this country enjoys peculiar advantages as a field for research, and that British workers have not wholly neglected the opportunities so liberally offered.

A. H.

ST. JOHN'S COLLEGE, CAMBRIDGE

October, 1932

NOTE ON THE SECOND EDITION

THE late Dr. Harker completed the revision of the text of his book only a few weeks prior to his death. His intention to provide a second preface was not to be fulfilled, and it is at his wish that I have undertaken the revision of the proofs for the press. In the new edition the original plan, and so far as possible the original text, have been preserved, but opportunity has been taken to make certain minor changes and corrections, and to incorporate reference to some later researches.

C. E. TILLEY.

CAMBRIDGE,

August, 1939.

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PART I

THERMAL METAMORPHISM

CHAPTER I

THERMAL METAMORPHISM: GENERAL CONSIDERATIONS

Scope of Subject—Plan of Treatment—Agents of Metamorphism—Conditions Controlling Thermal Metamorphism—Attainment of Chemical Equilibrium.

SCOPE OF SUBJECT

THE term 'metamorphism', i.e. change of form, is understood in geology as having reference to molecular and atomic configuration, as well as to visible shapes and relations; and it comprises therefore both mineralogical and structural rearrangements in rock-masses. Every branch of geology is, in fact, largely concerned with the phenomena of change in the material world, and it is evident that a study of rock-metamorphism, in the fullest sense of the word, would embrace a large part of the whole subject-matter of petrology. As conceived in the following pages, and in the usage of most petrologists, its scope is much less comprehensive, and it will be proper therefore to define at the outset the limitations to be observed.

The fundamental principle to be assumed as axiomatic is that the internal changes which take place in a rock are a response to changes in external conditions, and are to be interpreted as an effort to re-establish equilibrium under the changed conditions. The *conditions* which are relevant in this connexion are two: viz. temperature and stress. The province of metamorphism, as here understood, can then be defined as follows. We take as point of departure the various types of rocks known to us, such as can be handled and subjected to direct examination; i.e. rocks at ordinary atmospheric temperature and sensibly free from stress. We shall endeavour to follow the changes induced in like rocks where they have been exposed in nature to more or less elevated temperature and more or less intense stress. Since the two conditions are, at least theoretically, independent, we may distinguish *thermal* metamorphism, consequently upon rise of tempera-

groups, but 'contact' (i.e. purely thermal) metamorphism is definitely excluded. The crystalline schists are regarded as constituting a distinct great class of rocks, co-ordinate with the two other classes, igneous and sedimentary, their relation to these being consequently ignored.

While the descriptive method is rooted in the conception of *metamorphic rocks* as a distinct class of rocks defined by certain characters, that which I have called the genetic method starts from the idea of *metamorphism* as a certain class of changes, which may affect rocks of any kind and alter their characters. In its origin it attaches itself to the Huttonian doctrines as developed by Lyell, to whom the word metamorphism is due, and with the tenets of that school the notion of gradual progressive change was entirely in harmony. That from this logical starting-point no serious advance was made, is to be ascribed in part to that unfortunate neglect of the chemical and petrographical side which was long the reproach of British geology; but in truth little could have been accomplished on these lines with the knowledge then at command. The rapid development of physical chemistry in later years, and the successful application of the experimental method to the problems of petrology, have greatly altered the situation. On the foundation now being laid there may not improbably be built up in the future a complete theory of metamorphism on a rational and genetic basis.¹

The first serious attempt to discuss the process of metamorphism in relation to first principles was made by Van Hise,²; but the scope of his work is far wider than that here adopted, and a considerable part of his massive volume is devoted to such subjects as weathering, cementation, and ore-deposits. The later work of Leith and Mead³ is conceived on a plan no less comprehensive.

An important contribution to the theory of thermal metamorphism has been made by Goldschmidt⁴ in a memoir dealing primarily with the Oslo district. He makes direct application of the Phase Rule to determine the possible associations of minerals in a metamorphosed rock of given total composition. A rock completely metamorphosed in presence of a pervading solvent is regarded simply as a 'condensed' system of n components, and it is deduced that the number of distinct minerals which can exist together in equilibrium is then n , or at an

¹ Harker, Anniversary Address to the Geological Society, *Quart. Journ. Geol. Soc.*, vol. xxiv (1919), pp. lxiii-lxv.

² *A Treatise on Metamorphism, Monog. xlvii U.S. Geol. Sur.* (1904).

³ *Metamorphic Geology: a Text-book* (1915).

⁴ *Die Kontaktmetamorphose im Kristianiagebiet, Vidensk. Skr.* (1911). See also *Zeits. Anorg. Chem.*, vol. lxxi (1911), pp. 313-22.

invariant-point $n - 1$. The assumption of true chemical equilibrium cannot be universally admitted, and other assumptions underlying the author's reasoning have been criticized. To demur to Goldschmidt's argument, however, is not necessarily to combat his specific conclusions, which are generally supported by the observed facts; and the classification of different types of 'hornfels' to which he is led is of service as an ideal scheme. Nevertheless, since its application is only to rocks which have suffered total reconstruction, it throws no light upon metamorphism regarded as a progressive process.

Although we possess at present no complete theory of metamorphism based directly upon accepted principles, it is possible at least to prepare the way for such systematic treatment by marshalling observations and inferences with this ideal constantly in view. Such is the design of the present work, which to that extent may profess to aim at a rational or genetic treatment of the subject. Laboratory experiment, which has so greatly enlarged our understanding of the genesis of igneous rocks, is already being applied to some questions important in relation to metamorphism; while the known laws of physics and chemistry, based ultimately upon experiment, are always at our service.¹ Help from these quarters comes to supplement and reinforce the results of geological and petrographical inquiry; and it is by combining all these resources that we may best hope to gain an insight into the processes of rock-metamorphism. A philosophical treatment of the subject as a whole is not yet among things possible.

THE AGENTS OF METAMORPHISM

We read in the older text-books of geology that rocks are metamorphosed by the agency of heat and pressure, to which is commonly added the presence of water. The part played by water will be discussed later: regarded strictly, it is not to be reckoned among the controlling conditions of metamorphism, but makes part of the material in which metamorphism operates. For the rest, since we are concerned at present, not with the question of energy, but with the conditions of equilibrium, we may interpret 'heat' to mean rise of temperature. The remaining factor calls for more particular consideration.

The term 'pressure', as loosely used by the older writers, ignores a distinction which it is of the first importance to observe. On the one hand, the pressure at every point within a body may be the same in all directions. Since this is the only type of pressure-distribution that can be maintained in a fluid, it is conveniently distinguished as

¹ For a useful summary of these see Johnston and Niggli, *Journ. Geol.*, vol. xxi (1913), pp. 481-516, 588-624.

hydrostatic pressure, and in discussing the behaviour of liquids and gases the word pressure can usually be employed without ambiguity. This is true also of the customary operations of the laboratory, and the chemist can generally regard temperature and (hydrostatic) pressure as completely determining the conditions to which a given system is subjected. In metamorphism, however, we have to do with changes which proceed in the heart of a solid rock, and a solid is capable of sustaining pressure which, at a given point, is different in different directions. This is tantamount to saying that a solid, unlike a fluid, can sustain *shearing stress*. A simple analysis shows that any non-uniform pressure at a point within a solid body is equivalent to a simple (hydrostatic, pressure together with certain shearing stresses.¹ This mode of presentation is adopted in mechanics in discussing the correlation of stress and strain, because the 'modulus of compression', which connects uniform pressure with voluminal compression, and the 'modulus of rigidity', which connects shearing stress with deformation, are two independent constants. It is not less necessary in discussing molecular and atomic rearrangements within a body effectively solid, for here too the influence of simple pressure and of shearing stress must be carefully discriminated. The influence of hydrostatic pressure upon various transformations and chemical reactions can be expressed in terms of simple laws, but concerning the influence of shearing stress in this field much yet remains to be learnt. This is the more to be regretted, since shearing stress is undoubtedly a factor of great moment in controlling mineralogical changes in metamorphism, as it manifestly is also in respect of structural rearrangement.

In the following pages *pressure*, without qualification, will be understood to mean pressure of the simple hydrostatic type. The term *stress* properly comprises both pressure and shearing stress, but there will be little risk of misunderstanding if it is often employed for brevity in place of shearing stress.

The mathematician's analysis of stresses and strains is strictly applicable only to a homogeneous and isotropic body, and it is easy to see that uniform compression and pressure are not theoretically possible in a crystalline rock. If a cube of granite be subjected to uniform pressure from without upon its six faces, its mechanical status is different from that of a cube of glass under like external forces. Quartz and felspar are not equally compressible, and the compressibility of each crystal is different in different directions. The granite therefore cannot yield without some internal deformation and the

¹ Thomson and Tait, *Treatise on Natural Philosophy*, art. 682, and see below, Chapter X.

setting up of shearing stress. The same result follows from expansion or contraction with change of temperature. The point to be observed concerning these internal stresses is that, besides being of no great magnitude, they have no common direction, since the crystals lie in all ways indifferently. Consequently stress is in great measure annulled by mutual compensation. The small balance can be relieved by slight slipping of one crystal against another, by the opening of cleavage-cracks, by 'gliding' in the crystals of some minerals and bending in others, without appreciable change in the structure of the rock as a whole. Experiment shows indeed that the mechanical behaviour of a crystalline rock is, in the gross, much like that of an isotropic body, and that it conforms rather closely with Hook's law.¹

Of a very different order are the shearing stresses set up in rock-masses in response to the powerful external forces which arise in connexion with orogenic movements. The magnitude of these stresses is limited only by the crushing strength of the rocks, and in fact this limit is very often reached. Moreover, since the stresses here have a common direction, imposed by the external force-distribution, there is no mutual compensation. Relief can come only from very radical changes in the rock, which almost always involve mineralogical as well as structural rearrangement. The mineralogical changes induced under stress are dependent also on temperature, but we shall see that they differ in general from those changes which would take place at like temperatures in the absence of the stress factor.

Since the absence or presence of any important shearing stress is of prime significance in determining the mineralogical changes which follow when rocks are subjected to rise of temperature, and since it must evidently be of capital importance also in relation to the setting up of new structures, the distinction so implied will properly determine the plan of treatment of the whole subject. The first part of this volume will deal accordingly with thermal metamorphism, not complicated by the stress factor; the latter part will be devoted to metamorphism in which shearing stress enters as a ruling condition, with or without significant rise of temperature.

CONDITIONS CONTROLLING THERMAL METAMORPHISM

Shearing stress being absent or negligible, the factors which control thermal metamorphism are temperature and pressure (in the hydrostatic sense). Logically the two are co-ordinate, but in most cases

¹ Adams and Coker, *An Investigation into the Elastic Constants of Rocks, More Especially with Reference to Cubic Compressibility*, Carnegie Inst., Washington (1906).

a very moderate change of temperature is as effective as a very great change of pressure. For most purposes, therefore, we may regard the former as the dominant factor and pressure as merely modifying the influence of temperature. The grounds for this assertion will appear, if we examine very briefly and in general terms how various physical and chemical changes are dependent upon these two ruling conditions.

In the first place, a given mineral, supposed for simplicity to possess a stoichiometric composition, has a definite temperature-range of stability. When one of the limiting temperatures is passed, the mineral must undergo change, if equilibrium is to be maintained: alternatively, it may persist as a metastable form. The limiting temperatures include melting-points, inversion-points of dimorphous compounds, and dissociation-points. Dry fusion has no part in metamorphism, but an inversion-point in reversible dimorphism is strictly analogous to a melting point, and its dependence on pressure is expressed by the simple relation:—

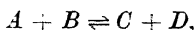
$$\frac{dT}{dp} = (v_{\alpha} - v_{\beta}) \frac{T}{L},$$

where T is the inversion-temperature reckoned from absolute zero, p is the pressure, L is the latent heat of inversion, and the expression in parentheses is the difference of specific volume between the higher and lower forms. The change from lower to higher is therefore promoted or retarded by increased pressure, according as it is accompanied by contraction or expansion. If the volume-change is small, pressure will have little effect, except in the possible case of the heat-change being also very small. Inversion may be greatly promoted, in the sense of its *rate* being accelerated, by the presence of some other body; but the inversion-temperature is not altered, unless this other body enters in solid solution. In irreversible or monotropic dimorphism there is no inversion-point: the lower form is merely metastable, and exists only by reason of an infinitesimally slow rate of inversion. Rise of temperature, by accelerating the rate, may bring about the change, but not at any determinate temperature. Here, too, a catalyser may greatly promote the change to the stable form.

Solution again is in all respects analogous to melting. The solubility of a given mineral in a given liquid is a function of temperature and pressure. It is increased or diminished by rise of temperature, according as heat is absorbed or liberated in the act of solution. The former is the more usual case, but we possess few data for rock-forming minerals. Increased pressure augments or diminishes solubility,

according as the volume-change and the heat-change in solution are of opposite signs or like sign ; but the little that is known from experiment suggests that, for solution of a solid in a liquid pressure is not usually of great moment.

In considering chemical reactions as controlled by temperature and pressure, we must distinguish between a balanced reaction and one which proceeds to completion. Suppose, first, that the total composition of the system remains unchanged, and consider a balanced reaction of the type :



where the letters represent single molecules of the four phases involved. The equilibrium arrangement is determined by the mass-action equation :

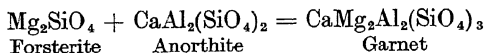
$$[A][B] = K[C][D],$$

where $[A]$ stands for the concentration of A , etc., and K , the reaction-constant, is a function of temperature and pressure. Its dependence upon these is such that a rise of temperature drives the reaction in that direction which involves absorption of heat, and an increase of pressure drives it in the direction that involves diminution of volume. If only solid and liquid phases be present, the volume-change is seldom very considerable, and only a very great pressure will have any sensible influence. It is otherwise when a gaseous phase is involved. Pressure will then have a very pronounced effect, in the sense of resisting the reaction by which the gas is liberated.

Suppose now, on the other hand, that one of the four phases can pass out of the system. There can then be no balance, but the reaction will proceed continually in one direction until that body is eliminated. Thus, if D be a gas, and if the circumstances be such that it can escape, the reaction will be driven in the direction from left to right until A and B are exhausted and C alone remains. The result will be the same if the reaction is one between bodies in solution and D is insoluble, so that it passes out of solution as soon as it is formed. Again, if all four bodies be soluble in different degrees, a like situation is reached as soon as the least soluble body arrives at the point of saturation.

It may be laid down summarily, that the changes which are promoted by rise of temperature are those which involve absorption of heat, and the changes which are promoted by increase of pressure are those which involve diminution of volume. If the latter of these two general laws is more frequently cited than the former, it is perhaps because the volume-change is more easily calculated than the heat-

change. The 'Volume Law' in its application to metamorphism may be illustrated by an example borrowed from Becke. In the equation :



the molecular volumes on the left side are $43.9 + 101.1 = 145.0$, and on the right 125.8 , giving a diminution of volume to the amount of 13 *per cent*. Here the molecular volumes are computed from the specific gravities of the minerals in the laboratory, and would be greater at higher temperatures, but would doubtless still show a difference of the same order. It follows that, if the reaction indicated is a possible one, it will be very sensibly aided by high pressure. It must be remembered, however, that the Volume Law merely formulates the effect of pressure as considered apart from other factors. We shall see later that its importance has sometimes been exaggerated by attributing to uniform pressure effects which are really connected with unequal pressure and shearing stress. It is doubtless very generally true that rocks are denser after metamorphism than before, but this cannot be credited wholly to the cause in question. Expulsion of volatile substances will tend to the same result.

ATTAINMENT OF CHEMICAL EQUILIBRIUM

There are other considerations to be weighed before we can with confidence apply the data of chemistry to concrete problems in rock-metamorphism. The investigations of the physical chemist are usually directed to determining the *equilibrium* configuration of a given system under varying conditions of temperature and pressure. But, while the changes induced in a rock in metamorphism are always in the direction of restoring equilibrium, we are not entitled to assume that equilibrium is necessarily established. It is certain that it is not always realized even when a rock has been totally reconstituted, and to the lower grades of metamorphism the limitation applies with greater force. This does not remove metamorphism from the province of chemical science, but it does counsel caution in the application of simple laws to complex cases. In another field, that of the crystallization of molten rock-magmas, we know that the imperfect attainment of equilibrium has far-reaching consequences, but it has not been found impossible to include these consequences in the general scheme of petrogenesis. Various features of metamorphosed rocks, notably the comparative rarity of zoned crystals, seem to indicate that equilibrium is here more promptly attained, or more closely approached, than in a crystallizing magma. The magma has the advantage of freer

diffusion, but this is more than counterbalanced by the fact that crystallization there proceeds with falling temperature, while the reverse is the case in metamorphism. It is a capital principle, to be abundantly illustrated in our study of metamorphism, that equilibrium is reached or approached far more promptly with rising temperature or increasing stress than with falling temperature or declining stress. Doubtless many of the chemical reactions characteristic of rock-metamorphism are theoretically reversible, but for the most part they are not in fact reversed when the conditions which induced them have passed away. Minerals belonging to the higher grades,¹ instead of reverting to other products, more usually remain to indicate, as it were, the high-water mark of metamorphism. Were it otherwise, any study of the subject on the petrographical side would be impossible, since it would have little material to work on.

The matter can be discussed in terms somewhat more definite. In addition to the data of temperature, pressure, and concentration, which theoretically determine a certain chemical reaction, we must take account also of the *rate of reaction*, and must recognize that the rate is in some cases excessively slow. If it be so slow as to be negligible the sensible result is that the reaction does not take effect. The comparison here is between the rate of reaction and the time during which the conditions favourable to it are maintained: an unlimited lapse of time after those conditions have ceased will be of no avail. The rate itself is dependent upon the conditions, and especially upon the temperature. According to Johnston and Niggli, it may be doubled by a rise of 10° , while a rise of 100° may perhaps increase it a thousand-fold and 200° a million-fold. For this reason it is chiefly in the lower grades of metamorphism that complication arises from the non-adjustment of equilibrium. Concerning the influence of stress upon the rates of reactions we know little, but it is probable that simple pressure is without sensible effect. More important is it to observe that a rate of reaction may be greatly accelerated by the presence of some body which apparently does not itself take part in the reaction, or at least does not enter into the resulting products. We are probably to infer that it plays an essential part in some intermediate reaction and is finally set free. Whatever be the true nature of this 'catalytic' action, it certainly has its importance in metamorphism. If by its means a rate, otherwise insensible, becomes sensible, the practical effect is that the catalyser induces a reaction which would not take place in its absence.

The change in the imposed conditions, temperature and pressure,

¹ The word 'grade' will be used always with reference to temperature.

which determines metamorphism, is a gradual and continuous change. If chemical equilibrium were constantly maintained, mineralogical reconstruction would likewise proceed steadily and continuously, keeping pace with the changing conditions. Something like this we may suppose realized in the higher grades of metamorphism, where rates of reaction are accelerated by high temperature. In the lower grades this cannot in general be true, for the process does not commonly start from equilibrium. The given rock, which we take as our point of departure, has in fact a past history. If, for instance, it be an igneous rock, some of the high-temperature minerals which compose it are not truly stable under the actual conditions, but survive only in virtue of that chemical inertia which has been indicated. If it be a sedimentary rock, the several minerals may be individually stable, but not in true equilibrium with one another. They remain unchanged merely because, under the actual conditions, the rate of any possible reaction is so small as to be sensibly *nil*. This is the case known as 'false equilibrium'.

The conception of metamorphism to be kept constantly in mind is that of something *progressive*. In response to rising temperature the substance of a given rock passes through a certain sequence of transformations, the stage actually reached depending upon the highest temperature attained. In the original rock, however, there are, in the most usual case, some constituents which are more susceptible of change than others, in the sense of being affected at an earlier stage of the rise of temperature. They may dissociate, or react with one another, or merely recrystallize. In an early grade therefore such a rock is only partially metamorphosed. It consists partly of new and recrystallized minerals, partly of *residual minerals* still intact. With continued rise of temperature these are in turn drawn into the sphere of the processes of metamorphism; so that in any advanced grade the rock may be regarded as totally reconstituted. The only noteworthy exception is that of the highly refractory mineral zircon, which can even survive complete dissolution of a rock which contained it.

The changes which take place in the earlier stages of metamorphism depend, then, upon the *initial mineralogical constitution* of the rock; but in an advanced grade all is determined by the *total chemical composition*, in conjunction with the given conditions of temperature and pressure, the past history of the rock being no longer relevant. When a new mineral has once come into being, or an old one has recrystallized, it is still, potentially at least, a party to all that happens thereafter with further rise of temperature. It may be called in a sense alive, in that it responds freely to suitable stimulus from without. Through the

medium of a common solvent—a matter which we have yet to consider—the several minerals present are maintained in chemical equilibrium with one another by a large number of balanced reactions among them. These reactions are balanced at any given temperature: rise of temperature displaces the balance, and may bring into play new reactions.

By rejuvenation of the several minerals, together with reactions between them, a rock, once reconstituted, is still being continually made over again with advancing metamorphism. The student should guard against importing into the discussion of metamorphism the conception of an 'order of crystallization', which is a prominent feature of igneous rocks. Even in the crystallization of a molten magma, conducted with falling temperature, it would be an error to suppose that a mineral, once crystallized, passes out of the province of chemical reactions: we know that it is sometimes resorbed or dissociated at a later stage. In metamorphism, which proceeds with rising temperature, such readjustment is not an exceptional but a universal incident, and the several constituents of a metamorphosed rock, apart from residual minerals, if any, are in effect of simultaneous crystallization. We have next to consider the mechanism by which this continual building anew of the rock is effected.

CHAPTER II

THERMAL METAMORPHISM: GENERAL CONSIDERATIONS

(continued)

The Rôle of Solution in Metamorphism—Limit set to Diffusion—Aureoles of Thermal Metamorphism—Some Illustrative Areas—Vitrification of Shales and Sandstones.

THE RÔLE OF SOLUTION IN METAMORPHISM

WHEN in discussing the processes of metamorphism, we speak of a chemical reaction between two minerals, such as calcite and quartz, we are using an elliptical expression. No sensible reaction can in general be verified at the contact of two crystalline bodies.¹ We are to suppose that the bodies in question enter into solution, and there suffer dissociation and reassociation, the new products finally passing out of solution. Even recrystallization of a single mineral, where no chemical reaction is implied, must usually be brought about by solution. The presence of some *solvent medium* pervading the rocks is therefore to be presumed as an essential part of the mechanism of metamorphism of any kind.

It is no less important to observe, however, that the solvent must be present in general only in *very exiguous quantity*. The kind of solution to which we make appeal is a *local and temporary solution*. Bodily dissolved, a rock would lose its identity, yielding not a metamorphosed product but a totally new rock. In thermal metamorphism at least, the preservation of various residual structures, such as the banding in sediments or the ophitic and other characteristic peculiarities of igneous rocks, shows that the rocks have in fact maintained their identity throughout the process. We are then to conceive a rock which suffers metamorphism as being worked over *gradually and piecemeal* by the very small quantity of solvent present, which is continually set free to act upon new portions of the rock. If metamorphism is a

¹ An interesting paper by N. W. Taylor and F. J. Williams treats of 'Reactions between Solids in the System CaO—MgO—SiO₂'. Here, however, the lime and magnesia were introduced as carbonates, yielding abundant carbon dioxide to act as a solvent; *Bull. Geol. Soc. Amer.*, vol. xivi (1935), pp. 1121-36.

slow process, this is due, not only to the tardy rate of some of the reactions involved, but to the small total amount of disposable solvent, which must therefore be used over and over again. When we say that mineral substances enter into solution, take part there in chemical reactions, and pass out of solution in new forms, we are not to conceive that the metamorphism of the rock as a whole falls into these distinct stages; but merely that such is the sequence of operations at any one spot in the rock, and is realized successively at different spots.

This is no imaginary picture. Its truth can be verified in that type of spotted slates ('Knotenschiefer' or 'Fruchtschiefer') which often figures as the lowest grade of thermal metamorphism in argillaceous sediments. When a rock has been completely transformed in the manner sketched, all trace of the earlier stages of the process is obliterated; so that in general all that belongs to solution is a closed chapter. In the case cited, however, the process has been left incomplete, local solution having taken place but not the correlative recrystallization. We then have the opportunity of observing the course of metamorphism as arrested at an early stage. The type of spotted slate in question has been studied by Hutchings¹ and others. The essential constituent of the spots is an amorphous, isotropic substance of a pale yellow colour, which can be regarded only as a glass (see page 24, Fig. 1, B). It may enclose minute new crystals, e.g. of rutile, which recrystallizes very readily. The glass, as such, is structureless, but has sometimes given rise to indistinctly cryptocrystalline matter, or is beginning to develop a finely flaky structure, with feeble depolarization. If devitrification has gone farther, there results a minutely crystalline mosaic which can be partly resolved into mica and quartz.

The interpretation of these phenomena can scarcely be in doubt. The first step in the metamorphism was *local solution*, beginning at many *isolated points* within the rock. This should have been followed by recrystallization, setting free the solvent to attack new portions of the rock-mass; but the crystallization of silicate-minerals demands time. In the actual circumstances the temperature attained has been high enough to initiate local solution, but the duration of the high-temperature conditions did not suffice for the complementary process of recrystallization. The dissolved spots passed therefore into a glassy or largely glassy state, just as an igneous magma will do with rapid cooling. In this glass, we must suppose, the small quantity of solvent is itself incorporated.

The principal solvent which officiates in the metamorphism of rocks

¹ *Geol. Mag.*, 1894, pp. 43-5, 64-8.

is doubtless the omnipresent water. Most inorganic substances are in some degree soluble in water, and in general the solubility is increased by rise of temperature. Not a few characteristic minerals of metamorphism—micas, chlorites, epidotes, amphiboles, idocrase, etc.—have hydroxyl or basic hydrogen as part of their constitution. This affords direct evidence of the presence of water during the metamorphism, though not a measure of the amount present. It teaches us, too, that the function of water is not always limited to the part of simple solvent, since it may also participate in chemical reactions. Even when no part of it enters into the final products, it may possibly have taken part in intermediate reactions. If we compare rocks in different grades of metamorphism, we see that water enters to a less extent into the constitution of the new minerals at the higher temperatures. This may be compared with the crystallization of an igneous magma, conducted likewise in presence of water but with falling temperature. There the earlier products of crystallization are all anhydrous; such minerals as hornblendes and micas come later; and minerals rich in water, such as analcime, appear only in the closing stages.

While the chemical action of water is essential to the production of particular minerals of metamorphism, its solvent action is universal, and may be regarded as its prime function. We find therefore no place for a special type of 'hydrothermal metamorphism', as distinguished by some geologists. With water as the chief solvent are associated other substances, which have a less general distribution, and figure usually in much smaller quantity. Here are to be reckoned borates, fluorides, chlorides, carbon dioxide, and others of less importance. Being more potent solvents than water, they may perhaps play a part by no means negligible, even when present in very minute quantity. It may be supposed, too, in view of their greater chemical activity, that they take part in essential chemical reactions to a greater extent than water does. Direct evidence of their action is seen where some part of the boron, fluorine, etc., has become fixed in certain new minerals; but the absence of such material trace does not preclude the possibility that these active bodies have had a share in the metamorphism, whether as catalysers or merely as solvents.

The critical temperature of water is 374° C., and this figure will not be much raised by a small admixture of other volatile substances. The critical pressure is for pure water about 200 atmospheres, equivalent to about 2,500 feet of rocks. It appears then that, while, under the ordinary conditions of thermal metamorphism, the solvent medium may possibly remain in the liquid state up to a temperature in the neighbourhood of 400° , we must suppose it to be gaseous at higher

temperatures, and therefore in any really advanced grade of metamorphism. The solvent power of liquid water falls off rapidly as the critical point is approached, but there seems to be little information concerning the properties of gaseous water above that point. It is true that many experiments are on record in which various substances have been heated with water in sealed vessels,¹ and from these it appears that numerous minerals have been deposited, as if from aqueous solution, at temperatures well above 400°. It must be remembered, however, that water and the associated volatile bodies, besides acting as solvents and fluxes, may take part in chemical reactions of a cyclical kind, i.e. may officiate as catalysers. There is experimental evidence that gases above the critical temperature have the power of dissolving non-volatile bodies, and that the solubility increases with rising temperature.² Although such investigations have not been extended to the rock-forming minerals, it is shown that silica is soluble in gaseous water, at least at temperatures above 700° C.

Concerning the source of those special volatile substances which may co-operate with the water a few words will suffice. We cannot in general suppose them to be derived from the material of the rocks which suffer metamorphism. It is true that tourmaline, for instance, is a widespread constituent of ordinary sediments; but the boric acid there contained is not only in very small relative quantity, but is already locked up in a highly stable combination. Detrital tourmaline recrystallizes readily in metamorphism, but with nothing to suggest that it enters into special relations with other minerals present. One class of rocks there is, which in this respect stands upon a peculiar footing. Partly calcareous sediments undergoing metamorphism are capable in certain circumstances of liberating abundant carbon dioxide, and may be said to provide a competent solvent from their own substance. This is one of the features which invest the metamorphism of such rocks with exceptional characteristics. Setting aside this special case, it appears from the mineralogical evidence that the distribution of volatile substances other than water is of a local kind. Moreover, it is localized in evident relation to igneous activity. Metamorphic minerals containing boron or fluorine or chlorine are found in general only near igneous intrusions belonging to the epoch of the metamorphism. At the immediate contact such distinctive minerals are sometimes very abundant, and are clearly related to a pneumato-

¹ For a useful summary of such experiments see Morey and Niggli, *Journ. Amer. Chem. Soc.*, vol. xxxv (1913), pp. 1086-1130.

² Greig, Merwin, and Shepherd, *Amer. Journ. Sci.* (5), vol. xxv (1933), pp. 61-73; Ingerson, *Econ. Geol.*, vol. xxix (1934), pp. 454-70.

lytic replacement, which has usually affected igneous and metamorphic rocks in common. We may infer with confidence that the more active solvents and mineralizers in metamorphism, carbon dioxide excepted, are of direct magmatic origin.

This is also true in the main of the water itself, for any extensive penetration of surface-water into the heated interior crust of the earth is not an admissible hypothesis. Free circulation is confined to very moderate depths, and capillarity necessarily ceases at the critical temperature.¹ In any but quite superficial rock-masses the contained water must be attributed to the same ultimate source as the other volatile bodies. Water, however, being present much more abundantly in igneous magmas than the rest, comes to have a much more general distribution in rocks at large. There is evidence that its degree of concentration varies locally, and that in a manner directly related to igneous intrusions; but this variation is superposed upon a general distribution, which has been attained cumulatively during preceding ages.

That part of the earth's crust which is the theatre of metamorphism is to be conceived therefore as everywhere permeated by a medium consisting of water with other volatile substances. In all places where the temperature is above the critical point, and at lower temperatures where pressures are not high, this pervading medium is in the gaseous state. In general extremely tenuous, it may attain a more notable concentration in the neighbourhood of igneous intrusions; and there also the more active volatile substances, elsewhere quite subordinate to water, may acquire enhanced importance.

LIMIT SET TO DIFFUSION

The physical properties of gases at high temperatures and under great pressures are very imperfectly known; but we may most probably conceive the general solvent medium as possessing a high degree of viscosity, with a density such as we associate normally with liquids.² Sparingly distributed through the rocks, it is held in capillary and subcapillary passages and in solid solution in the minerals of the rocks themselves. In the general case, anything of the nature of free circulation is quite precluded. In the shallowest levels of the earth's crust, where such circulation is possible, water acts as a carrier promoting hydration, oxidation, dolomitization, and many other processes which lie outside the province of metamorphism as here understood. In dynamic metamorphism, too, where it has been effected under a

¹ Johnston and Adams, *Journ. Geol.*, vol. xxii (1914), pp. 1-15.

² Compare Arrhenius, *Geol. Fören. Stock. Förh.*, vol. xxii (1900), p. 395.

thin cover, there is evidence of the carriage of material in solution, but this we may regard as a special case. In general the conditions prohibit flowing movement of the solvent medium, and any redistribution of material must be effected, not by molar, but by molecular flux, that is by *diffusion*. This is true equally of the solvent medium itself and of rock-substance which passes into solution, but there are important circumstances which discriminate the two cases.

We possess no knowledge of the numerical constants of diffusion in viscous media at high temperatures, but the form assumed by the fundamental law of diffusion itself makes it evident that redistribution by this process must always be very slow. The propagation of any sensible concentration beyond a very short distance will demand a very prolonged lapse of time. The diffusion of the volatile solvent through the earth's crust can become effective, despite the extreme slowness of the process, because it is perennially in progress, and the actual distribution at any epoch in the world's history has been gradually brought about during ages preceding. The diffusion of dissolved rock-substance presents a very different case. In general the solubility of a mineral in any sensible degree is dependent upon an elevated temperature, besides being augmented, as we shall see, by stress. Solution therefore, and consequently diffusion of dissolved material, are subject to the primary conditions which determine metamorphism. Here diffusion is not only a slow process, but is operative only during a limited time, the 'diffusivity' rising with temperature and stress to a maximum and falling off as these conditions decline. Migration or interchange of material within a rock undergoing metamorphism is consequently confined to very narrow limits.

The study of metamorphosed rocks amply confirms this conclusion, and makes it appear that the mineral formed at any given point depends upon the composition of the rock within a very small radius about that point.¹ The limit of effective diffusion thus indicated is commonly a small fraction of an inch. So, for example, in a banded sediment composed of thin layers of different nature—argillaceous, gritty, calcareous—metamorphism does not confuse all to one average type. The several narrow bands remain distinct, each represented by its own association of new minerals, even when a dozen alternations are included in the field of the microscope. It is needless to refer in this place to many other phenomena, which point to the same conclusion. The dynamic element in metamorphism, while introducing some modification, does not invalidate this generalization.

Diffusivity, as already remarked, is a function of temperature,

¹ Harker, *Journ. Geol.*, vol. i (1893), pp. 574-78.

increasing with rise of temperature. For this reason the latitude of migration of material, always small, becomes somewhat enlarged in the higher grades of metamorphism. Moreover, if we may legitimately picture the temperature-conditions as steadily waxing and then waning, it follows that, the higher the maximum temperature reached, the longer does the temperature remain above any assigned figure. One result is that the individual crystals of new minerals, or of old ones recrystallized, can attain larger dimensions.

Increase of grain size, if we suppose the total quantity of a mineral to remain unchanged, implies that this given quantity is by some means shared out among a smaller number of individual crystals. How this is effected is a question which demands closer consideration. It is to be remarked that an important function of the general solvent is to preserve a balance, not only between the different minerals present, but also between the several crystals of any one mineral. Crystals of the same kind but of different sizes, in presence of their saturated solution and within the range of effective diffusion, constitute a sensitive system, in that a slight cause may suffice to bring about corrosion of some crystals with correlative addition of material to others. Such a cause is found in *surface-tension*. Since the pressure due to surface-tension is proportional to the curvature of the surface, a small crystal is under greater stress than a larger one. Increased stress, as we shall have occasion to point out later, causes increased solubility. Material is therefore dissolved from the smaller crystals and deposited upon larger ones in their neighbourhood, until the smaller have disappeared. If a mineral is only sparingly present in the rock, the process will cease when the distance apart of the crystals exceeds the latitude of effective diffusion. If the mineral is so abundant that the crystals are necessarily close together, redistribution of material will continue, tending always to increasing coarseness of grain and also to uniformity of grain-size. The even-grained character is most noticeable in rocks of very simple constitution, such as marbles and quartzites. They illustrate also the coarser texture which goes with advancing metamorphism, and indeed in the highest grades a rock of any kind often shows a coarseness of grain comparable with that of a plutonic igneous rock.

The action described, depending upon surface-tension, is that to which Rinne¹ has given the name *Sammelkristallisation*, and he attributes to it an important part in various geological processes. In metamorphism it figures as one factor among others which go to determine the micro-structure of a reconstituted rock. It will suffice

¹ *Gesteinskunde*, 3rd ed. (1908), p. 167; 6-7th ed. (1921), p. 187.

here to note one way in which the ideal simplicity of the process may be disturbed. The approach to an equilibrium arrangement which we have pictured, depends upon the assumption that there is a fixed quantity of a given mineral in the rock. In the more general case there are reactions in progress, by which some minerals are being continually generated at the expense of others, and there can evidently be no finality so long as this continues.

AUREOLES OF THERMAL METAMORPHISM

The phenomena of thermal metamorphism are best studied in the rocks surrounding a large plutonic intrusion of a type not closely connected with orogenic movements. Here the heat, which is the proximate cause of the metamorphism, is of course drawn from the earth's internal store, but has been carried by an ascending molten magma. If, for a rough estimate, we suppose the temperature of intrusion to range from $1,000^{\circ}$ to 600° C., according to the nature of the magma, and assume 0.3 as the mean specific heat of the solid igneous rock, we have from 300 to 180 calories as the measure of the heat given out in cooling; to which must be added about 100 calories for the latent heat of fusion. From a large body of plutonic rock, therefore, an enormous amount of heat will be set free, and the whole of this passes by conduction into and through the surrounding rocks, raising their temperature in its passage.

This is not the only way in which rock-masses may become raised to an elevated temperature. As part of geological events of a large order, there can be a *direct* invasion of the earth's internal heat, conceivable as a general rise of the isothermal surfaces within the crust throughout a large tract. Igneous intrusion is likely to be an incident of this movement, but the intrusion cannot be regarded here as the cause of the high temperature. The rise of temperature affects the solid rocks, not only over a great areal extent, but to a great depth, and a very large increase of volume is therefore implied. The expansion cannot take effect uniformly, being free only in the upward direction, and so powerful shearing stresses are set up in the rocks. This case, therefore, falls under the head of what we distinguish as regional metamorphism. Even where the heating of rocks is brought about merely by an intrusion, if this is of very large dimensions, there must be a certain measure of shearing stress set up in the rocks of the aureole. In strictness, therefore, pure thermal metamorphism cannot be developed on a very large scale.

Under different and more local conditions the dynamic factor may figure, not as the consequence, but as the immediate cause of the

heating of rocks, viz. by the mechanical generation of heat in crushing. This is a case to be discussed later. It is evident that here too the element of shearing stress removes the effects beyond the province of that simple type of metamorphism which will first engage our attention.

This simple type is sometimes styled 'local' in contradistinction to 'regional' metamorphism; but pure dynamic metamorphism and effects resulting from the mechanical generation of heat have equally a local distribution. The term in common use among Continental geologists is 'contact-metamorphism', although the phenomena may be exhibited at a distance of miles from any igneous contact. Inasmuch as the effects are due, not to contact, but to heat and high temperature, the term *thermal metamorphism* seems more appropriate.

The belt of metamorphosed rocks surrounding a plutonic intrusion, conveniently styled a *metamorphic aureole*, has a width which depends upon more than one factor, but mainly upon the size of the intrusive mass. Since not all kinds of rocks are equally susceptible of change, we may expect the visible effects to extend farther outward in some rocks than in others, but in many instances this selective action is in fact little apparent. The aureole of the granite boss of Shap, in Westmorland, comprises grits, flags, slates, calcareous shales and tuffs, pure and impure limestones, basalts, andesites, rhyolites, and various pyroclastic rocks; but, if the first definite formation of new minerals be taken to mark the outer limit of the aureole, this can be drawn at about 1,200 or 1,300 yards from the granite-contact in very different rocks. The width so indicated is roughly equal to the semidiameter of the granite boss. The larger granite masses of Cornwall have aureoles up to two or three miles in breadth, and here the selective action is sometimes evident. At some places in Cornwall, indeed, effects of thermal metamorphism have been recorded even farther from any visible granite,¹ but the possible underground extension of the intrusions is to be taken into account. An intrusive mass like the Skiddaw granite in Cumberland, which shows only limited exposures but underlies the neighbouring rocks at a low inclination, has, for this reason, what appears a disproportionately large aureole of metamorphism. Its outer boundary, too, influenced by the varying surface-relief of the country, follows an irregular course on the map. In short, it is to be borne in mind that the aureole seen is merely the section by the actual ground-surface of a three-dimensional aureole.

The degree of metamorphism experienced at any place within an

¹ Effects have sometimes been ascribed to this cause, which belong truly to an earlier and quite independent regional metamorphism.

aureole must be supposed dependent, for a given type of rock, upon the highest temperature attained at that point; but with the proviso that the high temperature was maintained long enough for the possibly slow process of metamorphism to be completed. Accordingly we can note, in a general sense at least, an advance in metamorphism from the outer limit of the aureole up to the actual contact. The highest grade of metamorphism, attained close to the contact, stands in relation with the temperature of intrusion of the plutonic magma, which is highest for the most basic types and lowest for those of acid or specially alkaline composition.

There is, however, another factor which is of importance. The intruded magma not only supplies heat to the surrounding rocks, but may also furnish more or less copiously the water and other volatile bodies which play so essential a part in all metamorphism. It is noticeable how generally muscovite-bearing granites and pegmatites are surrounded by an important aureole of metamorphism. This is not due to a high temperature of intrusion, but to the richness of these acid magmas in gaseous constituents. If we look to the actual mineralogical changes induced, we shall see that the highest grades of metamorphism are found especially near basic and ultrabasic rocks, intruded at high magmatic temperatures. The transference of water, in the gaseous state, from an igneous magma into and through the surrounding rocks, while promoting metamorphism, may set no obvious mark upon the resulting products. It is otherwise when volatile bodies of much greater chemical activity pass in quantity from an igneous magma into the rocks immediately contiguous. Metamorphism proper then becomes complicated by pneumatolysis, involving an important amount of metasomatism. The discussion of this pneumatolytic element in metamorphism will be conveniently deferred, until we have dealt with the effects of simple thermal metamorphism in different classes of rocks. The special effects, it should be observed, are confined to the neighbourhood of an igneous contact, and are essentially dependent upon that situation. They might approximately be designated 'contact-metamorphism', had not that term already acquired a less suitable connotation.

If a metamorphic aureole embraces a varied succession of rocks, the progressive advance of metamorphism can be appreciated only in a general way, since there is no obvious term of comparison between the different rock-types. If the rocks are of one general type, the progress of metamorphism can be followed step by step; and, if there be frequent alternations of different rocks, the same end can be attained by confining attention to one type. In favourable circumstances it

is then possible to divide the aureole into successive zones of metamorphism, possessing distinctive characters and representing successive grades of metamorphism. This was first attempted by Rosenbusch¹ in the metamorphosed Palaeozoic slates known as the Steiger Schiefer round the granite mass of Barr-Andlau in the Vosges (Fig. 1). He distinguished three zones, from without inward: (i) *Knotenschiefer* or spotted slates, (ii) *Knotenglimmerschiefer* or spotted mica-schists, and (iii) *Hornfels*, rocks totally reconstructed. Other aureoles of

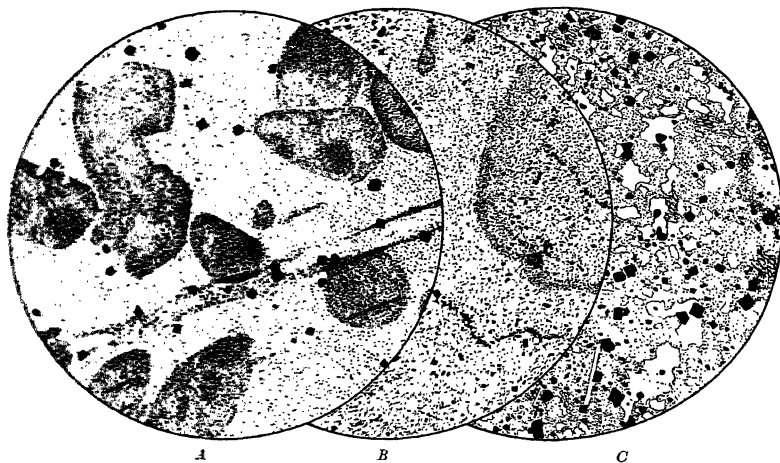


FIG. 1.—STAGES OF METAMORPHISM IN THE STEIGERSCHIEFER OF BARR-ANDLAU, VOSGES; $\times 25$.

A. Typical 'Knotenschiefer'. The spots are marked by aggregations of the disseminated carbonaceous matter, now reduced to graphite. The only distinct new mineral is a little magnetite, formed at the expense of haematite flakes.

B. A somewhat more advanced stage. The fine micaceous material, making the bulk of the rock, is recrystallized, but only on a minute scale. The spots here have a different significance, being places where recrystallization is incomplete and much amorphous matter remains (p. 15).

C. Andalusite-cordierite-hornfels. The rock is now visibly recrystallized throughout, and is composed of magnetite, quartz, mica, andalusite, and (altered) cordierite.

metamorphism have been divided into zones on somewhat similar lines. When these have been defined with reference to general descriptive characters, such as the coming in and disappearance of spotted structures, the divisions are necessarily arbitrary. It may be possible, however, to introduce an element of precision by taking as criterion of the outer limit of a zone the first appearance of some distinctive new mineral. The assumption required to make this valid is that mineral demands a certain minimum temperature for its forma-

tion, and is formed, in a rock of suitable composition, wherever that temperature has been reached. This would make the boundary as laid down an isothermal line, in the special sense that the maximum temperature reached in metamorphism was the same for points along that line. That for a given mineral there is a definite temperature of formation is doubtless true (with some allowance for varying pressure) in certain cases, e.g. where dimorphism of the reversible kind enters, and may be sufficiently near to the truth to be a serviceable assumption in some other cases.

SOME ILLUSTRATIVE AREAS

In the more special study of thermal metamorphism which follows, illustrations will be taken by preference from British examples; and it will be convenient to enumerate here, for purposes of reference, the principal metamorphic aureoles in this country of which we possess some knowledge. Those surrounding the Cornish and Dartmoor granites will be found described in various Memoirs of the Geological Survey of England and Wales.¹ The rocks metamorphosed are the Devonian slates, including calcareous slates, and the Culm Measures, besides sills of dolerite and spilitic lavas.

In the North of England, the Skiddaw granite² metamorphoses the Skiddaw slates and grits, while the aureole of the Eskdale granite is in the Ordovician volcanic series, and that of the Shap granite³ takes in a varied succession of Ordovician and Silurian rocks, sedimentary and volcanic. The Cheviot granite has metamorphosed the surrounding andesites of the Old Red Sandstone.⁴ The Galloway granites,⁵ intruded among Lower Palæozoic strata, are surrounded by well-marked belts of metamorphism, the rocks affected comprising grits, slates, and shales (some carbonaceous), cherts, and impure calcareous beds, besides the Ballantrae volcanic group.

¹ *Land's End* (1907), pp. 20-30; *Newquay* (1906), pp. 46-50; *Padstow and Camelford* (1910), pp. 63-77; *Bodmin and St. Austell* (1909), pp. 80-104; *Tavistock and Launceston* (1911), pp. 75-83; *Dartmoor* (1912), pp. 44-56; *Ivybridge* (1912), pp. 82-9. On Dartmoor see also Busz, *Neu. Jb. Min.*, B.Bd. xiii (1900), pp. 90-139, and *Geol. Mag.*, 1896, pp. 492-3.

² Harker, *Geol. Mag.*, 1894, pp. 169-70, and *Naturalist*, 1906, pp. 121-3; Rastall, *Quart. Journ. Geol. Soc.*, vol. lxvi (1910), pp. 116-40.

³ Harker and Marr, *Quart. Journ. Geol. Soc.*, vol. xlvii (1891), pp. 292-327, and xlix (1893), pp. 359-71; Hutchings, *Geol. Mag.*, 1891, pp. 459-63.

⁴ Kynaston, *Trans. Edin. Geol. Soc.*, vol. vii (1901), pp. 18-26.

⁵ Teall in *The Silurian Rocks of Britain*, vol. i, *Scotland* (*Mem. Geol. Sur. U.K.*, 1899), pp. 632-51; Miss M. I. Gardiner, *Quart. Journ. Geol. Soc.*, vol. xlii (1890), pp. 569-80; C. I. Gardiner and Reynolds, *ibid.*, vol. lxxxviii (1932), pp. 26-31.

The Caledonian plutonic intrusions of the Scottish Highlands break through members of the Dalradian and Moine series, which were already in the condition of crystalline schists. In the bordering tract, where the schists were in a low grade, the metamorphic aureoles are well marked; viz. about the Ben Cruachan mass,¹ the Garabal-Glen Fyne complex,² and that of Càrn 'Chois, near Comrie.³ The Deeside area is of interest for the striking effects produced by the Cairngorm and Lochnagar granites, especially in the Dalradian limestones.⁴ The nepheline-syenites of the Assynt district of Sutherland have metamorphosed the Cambrian dolomites,⁵ and like effects are to be observed near Tertiary intrusions of gabbro and granite in Skye.⁶ In the latter area may be studied also the thermal metamorphism of igneous rocks, both lavas and dykes⁷; and like phenomena are exhibited in great variety about the corresponding plutonic intrusions in the Isle of Mull.⁸

The Foxdale granite, in the Isle of Man, has a metamorphic aureole in the Manx slates.⁹ Some striking effects of metamorphism are shown by the Ordovician sediments bordering the Leinster granites at numerous localities in Counties Dublin and Wicklow, but there are at present few published accounts dealing with this area. It may be remarked in conclusion that interesting illustrations of thermal metamorphism, though limited in extent, are sometimes to be found near large sills and dykes of dolerite, such as the Whin Sill of Teesdale,¹⁰ the Plas Newydd dyke in Anglesey,¹¹ and the dolerites of Portrush¹² and Larne¹³ in Antrim.

The literature dealing with numerous European districts is too

¹ *Geology of Oban and Dalnally (Mem. Geol. Sur. Scot., 1908)*, pp. 139-52.

² Cunningham-Craig, *Quart. Journ. Geol. Soc.*, vol. lx (1904), pp. 25-6; Clough, *Geology of Couval (Mem. Geol. Sur. Scot., 1897)*, pp. 98-101.

³ Tilley, *Quart. Journ. Geol. Soc.*, vol. lxxx (1924), pp. 22-70.

⁴ *Geology of Braemar, Ballater, and Clova (Mem. Geol. Sur. Scot., 1912)* pp. 104-9; Hutchison, *Trans. Roy. Soc. Edin.*, vol. lvii (1933), pp. 557-92.

⁵ Teall, in *The Geological Structure of the North-West Highlands (Mem. Geol. Sur. Gr. Brit., 1907)*, pp. 453-62.

⁶ Harker, *Tertiary Igneous Rocks of Skye (Mem. Geol. Sur. U.K., 1904)* pp. 144-52.

⁷ *Ibid.*, pp. 50-4, 318-19.

⁸ *Tertiary and Post-Tertiary Geology of Mull (Mem. Geol. Sur. Scot., 1924)* M'Lintock, *Trans. Roy. Soc. Edin.*, vol. li (1915), pp. 25-31.

⁹ Watts, in *Geology of the Isle of Man (Mem. Geol. Sur. U.K., 1903)*, pp. 106-8.

¹⁰ Hutchings, *Geol. Mag.*, 1895, pp. 122-31, 163-9, and 1898, pp. 69-82, 123-31.

¹¹ Harker, *ibid.*, 1887, pp. 413-14.

¹² Cole, *Proc. Roy. Ir. Acad.*, vol. xxvi (B) (1906), pp. 56-66.

¹³ Tilley, *Min. Mag.*, vol. xxii (1929), pp. 77-86.

voluminous to be cited here. We may mention as of special interest the works of various writers on the Harz, Brittany, and the Predazzo district, as well as the researches of Rosenbusch in the Vosges, of Lacroix in the Pyrenees, of Beck and others in Saxony, and of Brögger and Goldschmidt in the Oslo district.

VITRIFICATION OF SHALES AND SANDSTONES

As already intimated, thermal metamorphism is not wholly confined to the aureoles of large plutonic intrusions. Any striking effects due to dykes or sills must, however, be regarded as exceptional. In the instances cited above the rocks invaded were of a kind peculiarly susceptible to metamorphism, such as impure calcareous sediments. In general the metamorphism bordering a minor intrusion is very limited, both in extent and in kind. It is seen in such changes as slight induration of argillaceous rocks, decoloration of red sandstones, and incipient marmorization of limestones.

There is, however, one special case worthy of notice, viz. the *vitrification* of argillaceous or arenaceous sediments for a few inches from their contact with a dyke or sill. We have already seen (p. 15) how a partially metamorphosed rock may be locally vitrified because cooling was too rapid to permit recrystallization. That the effect was there confined to isolated spots was due to the very small quantity of solvent present in the rock. At an igneous contact, however, it is possible that a sufficient supply of solvent, viz. water, may be supplied directly from a magmatic source, and the rock may become bodily vitrified. The effect extends only a few inches from the contact, and it is rare, because it requires a concurrence of favourable conditions. The high initial temperature demanded is realized only in basic or ultra-basic intrusions, and magmas of this kind are those least rich in water. Further, to ensure a relatively rapid cooling, the intrusion must be one of no great dimensions, and must be apart from any regular aureole.

Vitrification is found also in another case, viz. where fragments of some sedimentary rock have been enclosed in a basic lava or dyke or sill.¹ Here, however, complication is often introduced by some intermingling of the magma itself with the fused rock.²

Such superficial and local effects as the calcining of limestones and the charring of carbonaceous deposits at contact with a lava-flow do not call for particular notice. It is sufficient to observe how they

¹ The name *buchite* is applied to such vitrified rocks, or sometimes more specifically to vitrified sandstones.

² Thomas has described interesting examples from sills in the Isle of Mull: *Quart. Journ. Geol. Soc.*, lxxviii (1922), pp. 229-59.

differ from the phenomena of metamorphism effected within the earth's crust. Nor is it part of our plan to discuss solfataric effects, in which there enters commonly a large element of metasomatism. It is of interest to remark, however, that thermal metamorphism of the ordinary type has sometimes been produced locally by the passage of heated gases, without any intrusion of magma. Good illustrations of this are seen in the Isle of Rum.¹ The Torridon sandstone there exposed is traversed in many places by vertical crush-bands, ranging from mere fissures to fifty feet in width. Some of these have been injected in Tertiary times with basaltic magma, much modified by dissolving sandstone fragments; others contain no igneous material. The latter, as well as the former, give proof of thermal metamorphism which, though so narrowly limited, is of a high grade; and this can be attributed only to the passage of highly heated gases through the shattered rock.

¹ Harker, *Geology of the Small Isles (Mem. Geol. Sur. Scot., 1908)*, pp. 60-7.

CHAPTER ·III

STRUCTURES OF THERMALLY METAMORPHOSED ROCKS

Metamorphism Contrasted with Magmatic Crystallization—Residual Structures—Crystal Growth in the Solid—Force of Crystallization—Characteristic Structures of Thermal Metamorphism—Significance of Inclusions in Crystals.

METAMORPHISM CONTRASTED WITH MAGMATIC CRYSTALLIZATION

ROCKS which have become totally recrystallized in metamorphism present some obvious features of likeness to crystalline rocks of direct igneous origin. Many of the component minerals are common to the two classes. In textural and structural characters also, i.e. in respect of the size, shape, and disposition of the several constituents and their visible relations with one another, resemblances are easily perceived. Consciously or unconsciously, the student is liable to give to these distinctive characters in metamorphosed rocks the same significance that they bear in igneous rocks. It is of vital importance therefore to make it clear at the outset that such similarities of texture and structure do not import any real analogy. The determining factors are wholly different in the two cases; and although metamorphism may give rise to peculiarities which mimic well-known structures of igneous rocks, such as the ophitic and the porphyritic, the interpretation of them is in no wise the same.

We have to observe in the first place that the crystallization or recrystallization of minerals in metamorphism proceeds, not in a fluid medium, but *in the heart of a solid rock*, an environment which cannot fail to modify greatly their manner of growth. Further, the rock may be, during the process of recrystallization, in a condition of shearing stress imposed by external forces, and in the typical crystalline schists this additional factor has had a very important influence. These two postulates, the one universal and the other conditional, suffice to differentiate metamorphism fundamentally from the crystallization of a molten magma, and that in a manner which must make itself evident in distinctive structural characters.

There is another fundamental distinction to be remarked, which is of even greater moment. The crystallization of an igneous rock-

magma proceeds with falling temperature, and under such conditions a continuous readjustment of chemical equilibrium is seldom, if ever, realized in so complex a system. It must often happen that crystals which have separated at a higher temperature are no longer in equilibrium with a magma which has cooled and become changed in composition, and are, or ought to be, attacked by it. Bowen¹ in particular has discussed what he styles the Reaction Principle in Petrogenesis, and enforced its wide application. Although his conclusions may appear too sweeping, and the details of his formal scheme be open to criticism, the validity of the general argument can scarcely be questioned. None the less, a survey of the actual characters of igneous rocks in general, taking note of the complex mineralogical constitution of many common types and the frequency of zoned crystals, makes it evident that the reactions demanded by equilibrium have in most cases taken effect only very partially or not at all. In so far as this is true, the completed igneous rock as we see it represents a merely metastable arrangement. Be this as it may, the several constituent minerals belong to different stages of the process of consolidation. There is, for a given rock, a definite order of crystallization—including of course simultaneous crystallization of two or more minerals—and this order is plainly written in the visible structure of the rock.

In interpreting the structures of metamorphosed rocks the conception of an order of crystallization, with all that it implies, is to be totally discarded. The reconstruction of a rock in metamorphism proceeds *with rising temperature*, and all the facts go to show that, at least in any advanced stage of the process, adjustment of equilibrium in general keeps pace somewhat closely with the rise of temperature. Minerals formed at an earlier stage are, potentially at least, parties to the reactions which succeed at higher temperatures. If they do not change their composition or give place to other new minerals, they are still to be conceived as continually rejuvenated from stage to stage. The crystals are, as a rule, homogeneous, without zoning. Where crystals of two different new minerals come together, the boundary between them is not determined by priority of formation, for there is in this sense no priority, all the constituent new minerals of the rock being in effect of simultaneous crystallization.

This rough statement of the case will suffice to show that the textural and structural characters of metamorphosed rocks are determined by factors quite different from those which are operative in rocks of igneous origin. The subject is indeed one of some complexity, and it has been confused by the common practice of treating 'contact'

¹ *Geol.*, vol. xxx (1922), pp. 177-98.

(i.e. thermal) and regional metamorphism as two wholly unrelated classes of phenomena.

RESIDUAL STRUCTURES

Before discussing the characteristic new features developed in metamorphism, it is to be remarked that there is often, in the earlier stages at least, a survival of structures proper to the original rocks. These *residual structures*, aptly named by Sederholm 'palimpsest' structures, may vary from a clear transcript of the original to a mere shadowy reminiscence. Where internal differential movement is involved, pre-existing structures are likely to be soon obliterated, but in purely thermal metamorphism they may be still traceable in an advanced grade, despite mineralogical reconstruction of the rock. Their preservation is due to the very narrow limit set to diffusion in the lower grades of metamorphism; and their gradual fading out is a consequence of the more enlarged amplitude of diffusion which goes with higher temperature. It follows that there is a direct relation between the scale of magnitude of any original structure and its possible persistence with advancing metamorphism. The appearance of a clastic origin is very quickly lost in a fine-textured sediment, but remains evident longer in a coarse grit, while a pebbly structure is still to be detected in a high grade of metamorphism, after pebbles and matrix alike have been totally reconstituted (Figs. 26, *A*; 134, *B*). The larger structures of igneous rocks, such as porphyritic and amygdaloidal, may still be indicated in outline when all the original minerals have been recrystallized or replaced by new minerals (Figs. 42, *A*; 43). We can of course reason back from these facts of observation. Residual structures afford direct proof of the narrow limits of diffusion of material in metamorphism, and can be used to form estimates of those limits. To the geologist these relics have an obvious value as giving indications of the original nature of a rock, now represented, it may be, by an entirely new mineral-aggregate.

CRYSTAL GROWTH IN THE SOLID

We come now to those *new structures* which are set up in the process of metamorphism, and are exemplified in great variety in rocks which have suffered reconstruction under the conditions already glanced at. The critical study of this subject is a thing of recent years, and much is still to be learnt before a complete presentation of the matter can be attempted on systematic lines. So striking a feature as the foliation of crystalline schists naturally attracted attention at an early time, and its significance was discussed by Darwin in the middle

of the last century. Later investigation, with the aid of the microscope, made petrographers aware that, not only crystalline schists, but rocks recrystallized in thermal metamorphism have peculiarities of micro-structure which distinguish them from igneous rocks. Salmon in particular, describing the rocks of the inner ring of metamorphism about the tonalite of the Adamello Mountains, recognized a class of structures to which he gave the name 'contact-structures'. Among these he distinguished the simple mosaic type and various sieve-like, skeletal, and spongy arrangements arising from the interpenetration or inclusion of one mineral by another. He also used the epithet 'contact' as prefix to the name of a rock-type: thus a 'contact-pyroxenite' is a rock with the mineralogical composition of a pyroxenite, but with a micro-structure of a kind proper to a thermally metamorphosed rock. To connect such structural peculiarities definitely with the conditions of crystallization in a solid medium with rising temperature represents, however, a further step.

What long delayed a clearer understanding of the micro-structure of metamorphosed rocks was the tacit assumption that the rocks themselves play a merely passive part in the process of metamorphism. Despite the splitting of rocks by frost, the formation of crystals of pyrites in slate, of selenite in clays, and various other familiar phenomena, the powerful mechanical force which can be exerted by growing crystals received in this connexion only a tardy recognition. Its importance was first clearly recognized in 1903 by F. Becke,¹ in a paper dealing generally with the mineralogical composition and structure of the crystalline schists. The principles there plainly but very briefly set forth have been more fully developed by others, and especially by Grubenmann in his well-known work, also treating explicitly of the crystalline schists. It is a consequence of the complete divorce which Continental geologists have made between regional and 'contact' metamorphism, that the writers named do not distinguish those features which depend merely upon crystal-growth in the solid, and are therefore common to metamorphism of both kinds, from those which are related to a state of internal shearing stress maintained by external forces. For the same reason others, who have followed the lead given by Becke's exposition, have generally been slow to perceive how much of what he lays down for crystalline schists is no less true of thermally metamorphosed rocks also.² In accordance with the plan of the present work those peculiarities

¹ *Comptes Rendus ix Cong. Geol. Intern. Vienne*, 1903 (1904), pp. 553-70.

² Compare F. F. Emmons & G. F. Johnson, *Centr. f. Min.*, 1909, pp. 501-3; *Jahrb. f. Land.*, vol. xxx (1909), pp. 341-52.

which belong to the crystalline schists, being related to crystallization under special stress-conditions, are reserved for later consideration. We are concerned at present with the *structures of thermally metamorphosed rocks* only, depending on crystallization in the solid, free from any externally imposed shearing stress. In discussing these we can still accept Becke as our guide.

A mineral separating from an igneous magma grows, like a crystal of salt suspended in its saturated solution, by the tranquil addition of layer upon layer under no more restraint than is implied in viscosity and surface-tension. In metamorphism there is no such freedom. The growing crystal must make a place for itself against a solid resistance, and is to be conceived as *forcibly thrusting its way outward from its starting-point*. In consequence of the constraint so imposed, metamorphosed rocks of all kinds come to have a peculiar structure, or class of structures, for which we adopt Becke's term *crystalloblastic*, connoting the idea of sprouting or shooting (*βλαστάνω*).

The very great mechanical force that can be exercised by a growing crystal, which encounters resistance is illustrated by a simple experiment devised by Becker and Day.¹ They showed that a crystal of alum, growing in a saturated solution, can lift a heavy weight, and in so doing sustains a pressure of many pounds to the square inch. Indeed, geological observation and experiment alike go to prove that growing crystals are capable of exerting forces of the same order of magnitude as their own crushing strength.

In the experiment cited the material to build up the alum crystal was drawn from the surrounding medium at large; so that the lifting of the weight was to provide space for a certain amount of new material. In metamorphism, however, a crystal grows at the expense of part of the rock-substance, which it replaces, and there is in general no increase of total volume but often a certain diminution. In so far, therefore, as the crystal is built up at the cost of immediately contiguous material, it will experience no constraint in respect of volume but a definite constraint in respect of shape. In other words, shearing stresses will be set up.² Actually, as we have seen, interchange of material can take place within certain narrow limits; and such readjustment, proceeding concurrently with crystal-growth, will in some measure reduce or relieve the stress. Despite such accommodation, it is evident that, as reconstruction proceeds in the rock, and the

¹ *Proc. Wash. Acad. Sci.*, vol. vii (1905), pp. 283-8; *Journ. Geol.*, vol. xxiv (1916), pp. 313-33.

² The alum crystal was likewise subjected to shearing stress, being loaded above but free at the sides.

newly-formed crystals come to impinge upon one another, shearing stresses must inevitably be set up, and potentially stresses of considerable intensity. Now there are several ways in which these potential stresses may be actually relieved to a greater or less extent, and we shall see that these various devices are reflected in the multi-form peculiarities of structure met with in metamorphosed rocks. In fine, the key to the interpretation of these structures is to regard them as *contrivances for evading or minimizing the internal stresses set up by crystal-growth in a solid medium.*

FORCE OF CRYSTALLIZATION

Accepting Becke's 'force of crystallization' (Kristallisationskraft) as a definite property of a growing crystal, we must expect to find, first, that it is a *vector property*, differing in intensity in different crystallographic directions; secondly, that it is a *specific property*, differing in different mineral species; and, thirdly, that, like other properties of crystals, it is a *function of temperature*. Each of these principles has its importance in relation to the structures of metamorphosed rocks.

In proportion as the force differs sensibly in different crystallographic directions, and according as such force is called into play by resistance, the effect should be apparent in the shape assumed by the completed crystal. This is in all cases of a very simple kind. There is here little of the variety of habit shown by some pyrogenetic minerals; still less the richness in facets seen on crystals grown from aqueous solution in geodes and fissures. Crystal-boundaries of any kind are much less general than in igneous rocks. Where they are found, the principal, and commonly the only, faces present are those which are parallel to well-marked cleavages; and we may infer that the force of crystallization is greater along than across a cleavage. A large proportion of the minerals of metamorphism fall accordingly under one or other of two types; some having the tabular or flaky habit which goes with a single perfect cleavage, as in the micas; others the columnar or acicular habit which goes with two good cleavages, as in the amphiboles. Very commonly the mica-flakes show ragged edges, and the prisms of amphibole are devoid of terminal planes. Twinning is decidedly less frequent in metamorphic than in pyrogenetic minerals, and in particular the plagioclase feldspars are often free from albitelamellae.

The tabular and columnar forms are familiar, for the appropriate minerals, in crystals grown freely from a molten magma, but the characteristic habit is very decidedly exaggerated in crystals developed in a solid rock. There is another point of difference. In igneous rocks

the unequal development in different directions is strongly marked only in microlites, and tends to disappear in full-grown crystals: in metamorphosed rocks the peculiarity of habit, often little noticeable at first, becomes more pronounced as the crystals continue to grow in the face of resistance.

Such unequal growth in the heart of a solid rock must manifestly set up internal shearing stresses. If, for a mineral making up a considerable part of the rock, the crystals had a common orientation, these stresses would be additive. By a different arrangement, in

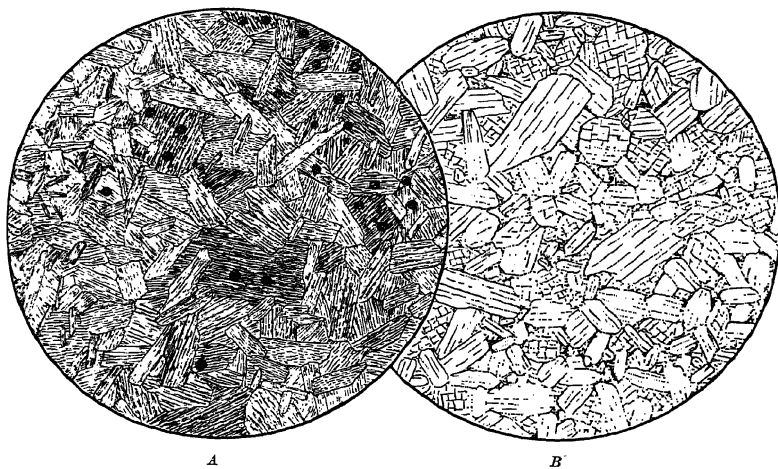


FIG. 2.—DECUSSATE STRUCTURE; $\times 23$.

A. Biotite-Hornfels, De Lank, near the Bodmin Moor granite, Cornwall. The dark spots are 'haloes' surrounding radioactive inclusions. See also Figs. 10, B, etc.
 B. Wollastonite-rock, Moonbi, New South Wales. See also Figs. 30, B, etc.

which corresponding axes of contiguous crystals lie in diverse directions, the stresses can be made in great measure to cancel one another by mutual accommodation. This is the arrangement typically exhibited in thermally metamorphosed rocks, and the micro-structure described, a criss-cross or *decussate* structure, is for such rocks highly characteristic. The component crystals lie in all directions; *not* at random, by the operation of a mathematical law of chance, but as part of a definite mechanical expedient for minimizing internal stress. This peculiar structure is most noticeable in a rock which is composed largely of minerals with a flaky or a columnar habit (Fig. 2). The interlacing of the little scales or prisms imparts to a 'hornfels' of this type a remarkable toughness and a distinctive kind of fracture.

The decussate structure is, however, by no means universal, even in rocks containing abundant mica. Our argument has assumed that the rock had originally no structure of the kind that implies weakened cohesion in a particular direction. The conditions are different in the earlier stages of metamorphism of a shale or slate which possessed a marked fissility, due either to bedding-lamination or to superinduced cleavage. As their fissile property attests, such rocks offer much less resistance along the bedding or cleavage than across it. Until this difference is obliterated by total reconstruction of the rock, new



FIG. 3.—STRUCTURES OF HIGHLY METAMORPHOSED SEDIMENTS; $\times 23$.

A. Biotite-Hornfels, inclusion in nordmarkite, Grorud, Norway. The flakes of biotite have the typical decussate arrangement.

B. Garnet-Biotite-Schist. Ordovician slate near a granite-contact, Glendalough, Co. Wicklow. Here the flakes still retain a parallel arrangement which marks the original

are generated and grow in a medium having peculiar mechanical properties. The flakes naturally push their way in the direction of least resistance, and so acquire a regular parallel orientation. The parallel structure in this case has in fact precisely the same significance as the decussate structure in the other case; i.e. it is a contrivance to elude the setting up of internal shearing stress. The parallel

ion may persist as a residual structure into a higher grade of metamorphism but is ultimately lost. Indeed, schistosity arising in this way is essentially a residual effect, perpetuating and sometimes accentuating an initial property of the rock. The schistosity which characterizes so many types of rocks in regional metamorphism

is, on the contrary, a new property with a direction imposed by external forces. The immunity from externally provoked stress which we have postulated in thermal metamorphism is, however, not absolute; and in a broad aureole bordering a large intrusive mass a tendency to parallel orientation from this cause is sometimes observable in highly metamorphosed rocks (Fig. 3, *B*).

Parallel arrangement of mica-flakes as a residual structure is related, not necessarily to the general lie of the bedding, but to the direction of lamination at the spot, which may have been affected

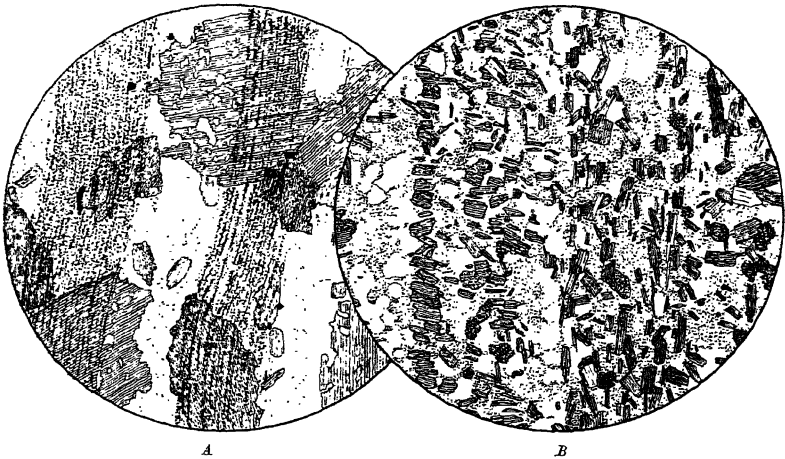


FIG. 4.—METAMORPHOSED SLATES PRESERVING BANDED STRUCTURES; $\times 25$.

A. Manx Slate near an aplite dyke, Crosby, Isle of Man. Shows large irregular flakes of biotite in a matrix of fine sericite and quartz. Trains of inclusions, marking the original lamination, pass undisturbed through the biotite.

B. Highly metamorphosed Devonian slate enclosed in the St. Austell granite, Cornwall: essentially of biotite, some muscovite, altered cordierite, and quartz. The mica-flakes have a definite orientation, in some bands parallel but in others transverse to the original bedding.

by contortion on a small scale. Such disturbance has sometimes been localized in certain narrow bands which were unusually yielding, giving rise there to an arrangement of new-formed mica-flakes transverse to the bedding (Fig. 4, *B*).

CHARACTERISTIC STRUCTURES OF THERMAL METAMORPHISM

Despite mutual accommodation, crystals starting from neighbouring points and thrusting out, each from its own centre, necessarily come into competition in a struggle for space, or more accurately for shape. In a completely reconstituted rock the shape of each crystal

has been determined by its encounters with its immediate neighbours. If all are of the same mineral, as in a pure marble or quartzite, they compete on equal terms, and no one is able to assert its natural crystal outline against its neighbours. The compromise results in a mosaic which, as seen in section, is made up of polygonal or partly interlocking elements of approximately equal size with sutural junctions (Fig. 29, below). A rock composed of two or more minerals shows a like structure, if the several minerals do not differ sensibly in their force of crystallization. Where any pronounced difference in this respect exists, the simplicity of relations is modified accordingly, the stronger mineral being able, in greater or less degree, to insist upon its natural development at the expense of its weaker neighbour.

This, it will be observed, is essentially different from the mutual relations between the minerals of an igneous rock, determined by the order in which they have crystallized. That is not a fixed order for all igneous rocks, but depends upon the relative proportions of the several minerals present as well as upon their specific properties; so that in one rock augite is idiomorphic towards felspar and in another the reverse. In metamorphism, as has already been laid down, the conception of an order of crystallization finds no place. Rather, in a rock totally reconstituted, we may assume a practically simultaneous crystallization of all the minerals involved (p. 30). If we accept this reasoning in its entirety, and suppose that the rock retains no trace of its past history, it follows that the mutual relations of the different crystals must be fixed solely by specific properties of the minerals themselves. The determining factor is, in short, the force of crystallization, which is found to differ widely in different minerals. The strongest, such as rutile and spinel, constantly make good their claims against all competitors, and usually exhibit good crystal-boundaries; the weakest minerals in this sense, such as the potash-felspars, are defeated in the struggle, and never develop their natural forms; for any mineral in general the issue depends upon its own force of crystallization as compared with that of the contiguous minerals, its immediate competitors. Since the terms 'idiomorphic' and 'xenomorphic' carry a connotation which is proper to igneous but alien to metamorphosed rocks, we shall adopt in their stead the terms used by Becke, primarily in connexion with the crystalline schists, *idioblastic* and *zenoblastic*. A stronger mineral is idioblastic against a weaker one in contact with it, and the relative force of crystallization of the several minerals in a rock can therefore be determined from their mutual relations. Becke, and after him Grubenmann, have that the constituent minerals of the crystalline schists can in

this way often be ranged in an order of relative strength, to which they give the name *crystalloblastic series*. The minerals of thermally metamorphosed rocks can likewise be at least approximately ranged according to the same property, i.e. in a list beginning with the strongest and ending with the weakest. Since some of the minerals are found only in certain classes of rocks, it is more convenient to make two lists.

In Argillaceous and Arenaceous Rocks

Rutile, pleonaste ;
Garnet, sillimanite, tourmaline ;
Magnetite and ilmenite, andalusite ;
Muscovite, biotite, chlorite ;
Plagioclase and quartz, cordierite ;
Orthoclase and microcline.

In Calcareous and Igneous Rocks

Spinel, spinel minerals, pyrites ;
Wollastonite, lime-garnet, apatite ;
Magnetite and pyrrhotite, zoisite and epidote ;
Forsterite and chondrodite, hypersthene and diopside, chalybite
and dolomite ;
Scapolite, albite, muscovite, biotite and phlogopite ;
Tremolite, idocrase and calcite ;
Plagioclase, quartz, orthoclase and microcline.

The order here set down will be found to hold good very generally, but is not to be accepted as a rigidly fixed standard. It is probable that the relative crystallizing strength of different minerals may be modified by factors which are not easily taken into account, such as pressure and the concentration of a solvent ; but the principal cause of exceptions or apparent exceptions to the rule is to be found in the effects of retrograde metamorphism. If a mineral has been produced as a pseudomorph during the declining phase of metamorphism, its visible form and relations are determined, not by its own properties, but by those of the mineral which it has replaced.

In works dealing with the crystalline schists an accepted nomenclature is in use for describing the varied micro-structures there encountered. Some of the terms are equally applicable to simple thermal metamorphism, inasmuch as the structures which they denote arise merely from crystallization in the solid, and are not necessarily related to shearing stress impressed from without. The simplest type is the *granoblastic*, answering to the mere mosaic arrangement which has

been noticed. It is necessarily modified when minerals of pronounced tabular or columnar habit make a noteworthy part of the rock, and, as we have seen, more than one variety of structure can then be recognized. In the tough close-textured type of rock properly styled 'hornfels'² the decussate arrangement prevails, while the mica-schists are characterized by a parallel disposition of the mica-flakes. Some more special structures have received convenient names. In the *porphyroblastic* some one mineral makes crystals of conspicuously larger size than the other constituents of the rock (Figs. 4, *A* ; 5, *B*).

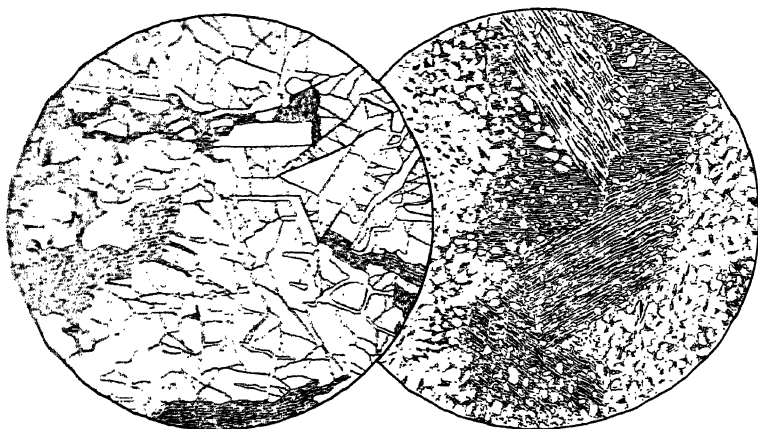


FIG. 5.—SPECIAL STRUCTURES IN METAMORPHOSED ROCKS; $\times 23$.

A. Diablastic structure: an intergrowth of andradite garnet, colourless axinite, and green hornblende in a metamorphosed dolerite near Falmouth.

B. Poeciloblastic structure in porphyroblasts in biotite-cordierite-hornfels, Riet-
v. N. of Parys, Transvaal.

term *diablastic* comprehends various intergrowths of two or more minerals, whether parallel or radiate or on some less regular plan (Fig. 5, *A*). In the *poeciloblastic* or 'sieve'-structure, which often with the *porphyroblastic*, the crystals of one mineral enclose smaller crystals of another (Fig. 5, *B*). The form of these words should remind the student that, for instance, the *poeciloblastic* structure in metamorphosed rocks has only a superficial resemblance to the *poecilitic* in igneous rocks, not a real analogy.

² This word, however, is often employed in so wide a sense as to lose any precise meaning, and some writers have affronted the English language by using 'hornfels' as a verb

We may go farther than this. These terms themselves, as applied to metamorphosed rocks, are to be understood as having merely a descriptive, not a genetic signification, for the structure denoted by a given name may arise in more than one way. Doubtless the principle of minimizing internal stress may often furnish the key. Competing crystals of different minerals may lessen the stress by a compromise which takes the form of interpenetration; or a large growing crystal encountering small crystals of other minerals may find it easier to swallow them than to thrust them aside. Very often, however, the explanation is to be sought in some earlier stage of the progress of metamorphism. Where two minerals are seen intimately intergrown, or one mineral is crowded with inclusions of another, it is probable that the two have often been formed as joint-products of some reaction, and have not yet been able to disentangle themselves.

SIGNIFICANCE OF INCLUSIONS IN CRYSTALS

In the earlier stages of metamorphism, however, inclusions are of a residual nature, representing material which could not be incorporated in the new-formed minerals. The original lamination of a finely banded sediment is often indicated by trains of minute inclusions of this kind (Fig. 4, *A*). If they are of a mineral such as graphite, which does not take part in chemical reactions, they may persist into an advanced grade, though they are liable to be disturbed by growing crystals of a strong mineral.

Growing crystals endeavour to clear themselves by expelling foreign inclusions of any kind, but their power to do so depends upon their inherent force of crystallization. A very weak mineral, like cordierite, may remain almost to the last crowded with inclusions. In a mineral of moderate strength, like scapolite, the elimination of inclusions often goes hand-in-hand with the development of crystal shape (Fig. 6, *A* and *B*). It should be remarked, however, that the force of crystallization is effective only when it is called into play by resistance, as growth proceeds. So even a strong mineral, such as garnet, often shows a nuclear portion full of residual inclusions, while the marginal part of the crystal is clear. This contrasts with the peripheral arrangement of inclusions so common in the crystals of igneous rocks. The dependence of force of crystallization upon temperature also has its application here. In a very high grade of metamorphism all but the weakest minerals tend to be free from inclusions, always excepting such as are being currently generated by high-temperature reactions.

We have seen that the force of crystallization, upon which the

THERMALLY METAMORPHOSED ROCKS

expulsion of inclusions depends, is a vector property. An instructive case is that in which a growing crystal has been able to brush aside foreign material, but not completely to eject it; the result being that trains of inclusions remain caught in the crystal along certain directions in which the force was least effective. The chiasolite variety of andalusite is a familiar example, and comparable phenomena are to be observed less frequently in cordierite,¹ staurolite,² and garnet.³ Of these four minerals, garnet stands very high in the crystalloblastic series and cordierite very low, while the other two are of medium

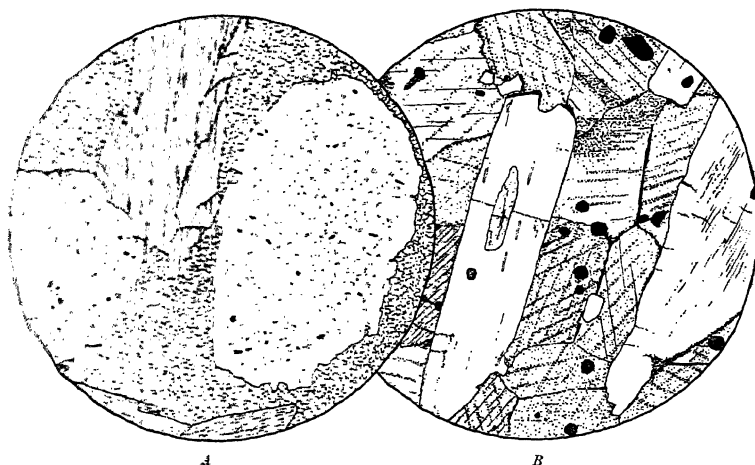


FIG. 6.—SCAPOLITE IN METAMORPHOSED LIMESTONES, from the Pyrenees; $\times 25$.

A. Puzos, Hautes Pyrénées: showing scapolite (dipyre), with numerous minute
and green actinolite.

B. : a coarsely crystalline limestone enclosing clear crystals of
and grains of pyrrhotite. In this higher grade the scapolite is cleared of
and has developed crystal outlines.

strength. What they have in common is an exceptional inequality of the forces in different crystallographic directions.

The peculiar features of *chiasolite* have been often discussed.⁴

¹ *Journ. Sci. Coll. Tokyo*, vol. iii (1890), pp. 313-34.

and Pratt, *Amer. J. Sci.* (3), vol. xlvii (1894), pp. 87-9.

² Renard, *Bull. Mus. Roy. Belg.*, vol. i (1882), pp. 18-19, and plate I, fig. 1;

y, *Mél. Phys. Chim. St. Pétersbourg*, vol. xii (1887), pp. 639-45.

rbaeh, *Zeits. Deuts. Geol. Ges.*, vol. xxxix (1887), pp. 632-8; Becke,

, vol. xiii (1892), p. 256; Sederholm, *Geol. Fören. Stockh.*

. xviii (1896), p. 390; Flett, *Geol. Lower Strathspey (Mem. Geol. Sur.*

), pp. 54-6; Mawson, *Mem. Roy. Soc. S. Austr.*, vol. ii (1911), pp.

The dark area in the centre (Fig. 7) represents the nucleus of the crystal, unable at that stage to free itself from inclusions. Subsequent growth has been effected by a thrusting outward, which was most effective in the directions perpendicular to the prism-faces. Much of the foreign matter brushed aside in this growth accumulated on the edges of the prism, and was enveloped by the growing crystal. The arms of the dark cross represent thus the traces of the prism-edges as the crystal grew. Finally, re-entrant angles may be left, but more usually these are filled in by the latest growth of the crystal, remaining

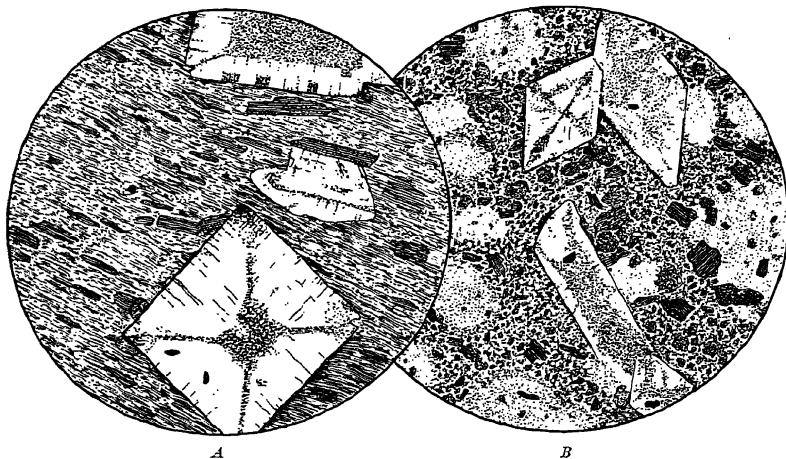


FIG. 7.—METAMORPHOSED SKIDDAW SLATES WITH CHIASTOLITE, CUMBERLAND; $\times 23$.

A. This rock has not yet lost the parallel arrangement of the new-formed flakes of biotite.

B. Chialstolite-Cordierite-Biotite-Hornfels, representing a higher grade of metamorphism. The cordierite is still in ill-defined round grains, which contain inclusions of biotite.

full of inclusions. A longitudinal section of the crystal would show the arrangement of inclusions as modified by the thrusting forth in the direction of the long axis. The streaming out of trains of inclusions away from the centre presents almost a visible picture of the operation of the forces of crystallization. It is in marked contrast with the concentric zones of inclusions common in the crystals of igneous rocks, Chialstolite affords also an impressive indication of the magnitude of the forces developed in crystal growth in the solid, for these forces have often been sufficient to shatter the crystal itself. The cracks follow the prismatic cleavage, but only one of the two cleavages is

opened in each sector (Fig. 7, *A*). This feature is most clearly exhibited when the crystals enclose an unusually large quantity of foreign matter.¹

A very prevalent feature of *cordierite* is the pseudo-hexagonal habit with six-fold twinning, and it is in connexion with this that a regular arrangement of inclusions is sometimes found. Kikuchi has given the name 'cerasite' to this variety of cordierite. The inclusions are grouped along hexagonal pyramids with apex at the centre of the crystal and bases on the basal planes (Fig. 8, *A*). In *staurolite*² a

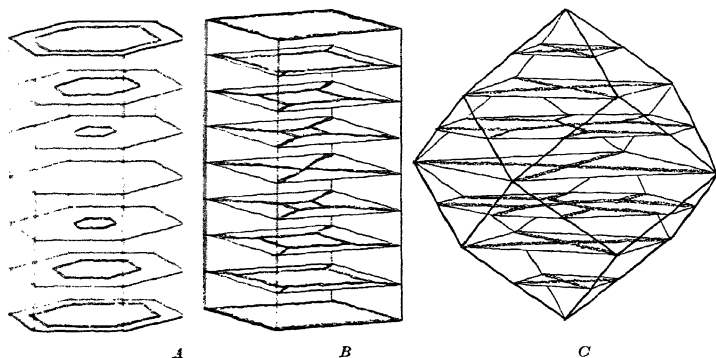


FIG. 8.—REGULAR ARRANGEMENT OF INCLUSIONS IN CRYSTALS, *Illustrated by a Series of Sections Parallel to the Basal Plane.*

A. Cordierite. *B.* Staurolite. *C.* Garnet.

regular pattern is not often seen. The inclusions are ranged along rhombic pyramids having apices at the centre and bases coincident with the basal planes of the rhombic crystal, and also, outside these pyramids, along median planes parallel to the two pinacoids (Fig. 8, *B*). In *pirret* too any special arrangement is not common. It is seen in manganese-garnets from the Ardenne and the Urals, and may sometimes be observed in the garnet, likewise manganiferous, of the New Galloway aureole. The inclusions are here distributed along twelve pyramids with apices at the centre and bases on the dodecahedral faces³: in other words, along the traces of the edges of the growing dodecahedral crystal (Fig. 8, *C*).

Sederholm, *Geol. För. Förh.*, vol. xviii (1896), pp. 390-3, with

¹This is a mineral especially characteristic of crystalline schists, but is included here for the sake of completeness.

²Karpinsky, *loc. cit.* Renard states erroneously that they lie along the principal planes of symmetry. See also Raisin, *Quart. Journ. Geol. Soc.*, vol. lvii (1901), p. 64, fig. 3.

CHAPTER IV

THERMAL METAMORPHISM OF NON-CALCAREOUS SEDIMENTS

Constitution of Argillaceous Sediments—Lower Grades of Metamorphism in Argillaceous Sediments—Medium Grades of Metamorphism in Argillaceous Sediments—Higher Grades of Metamorphism in Argillaceous Sediments.

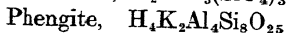
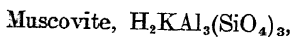
CONSTITUTION OF ARGILLACEOUS SEDIMENTS

BEFORE attempting to follow the course of metamorphism in rocks of various kinds, it will be proper to make some inquiry into the constitution of the rocks prior to metamorphism. How that constitution has been acquired is a question which lies outside our province, and will be dealt with only summarily. Sedimentary deposits are derived, by one or more removes, from crystalline rocks. They are the result of destructive action, partly mechanical and partly chemical, including biochemical, together with a redistribution of the various products. This redistribution, too, is in part mechanical, in part chemical in its operation; for it includes the sorting of finer from coarser detritus by running water, the separation of soluble from insoluble constituents, and secretion by organic agency. The solid particles derived from the chemical destruction of crystalline minerals are in general much smaller than the grains which result from mere mechanical disintegration; and consequently a separation between finer and coarser material is roughly a separation between decomposed and undecomposed. The one goes to make clays and the other sandstones. The argillaceous sediments represent then, as a first approximation, the products of chemical degradation of the parent rocks, or rather the insoluble residue of those products. There is, however, a variable admixture of mechanical detritus, chiefly of the finest washings of quartz.

Note first that, while some small part of the lime from feldspars and pyroxenes may be fixed in secondary epidote, etc., the bulk of the lime goes into solution as carbonate. Redistribution of dissolved material differs from mechanical transport in that there is no limit to its range, and most of the carbonate goes to make limestones in

distant areas. Apart therefore from an actual admixture of calcareous material, argillaceous sediments are notably poor in lime. Of magnesia, on the other hand, derived from the destruction of olivines, pyroxenes, amphiboles, and biotites, only a small part is dissolved as carbonate, and this constituent passes generally into minerals of the serpentine and chlorite groups. The original silicate compounds contained iron in the ferrous state replacing magnesia and sometimes in the ferric state replacing alumina. There is less of this replacement in the resulting serpentines and chlorites; so that much of the iron is set free as oxide, its final form being a hydroxide which for convenience we may name limonite. This too is the ultimate representative of most of the iron-ore minerals of the parent rocks. The titaniferous iron-ores yield in addition granular sphene and perhaps rutile, but the minute rutile-needles which are so characteristic a feature of slate-rocks come from the destruction of biotite (Fig. 69, B, below).

The alteration-products of the alkali-feldspars contribute largely to the composition of argillaceous sediments, and it is unfortunate that their true nature is involved in much obscurity. If we set aside the china-clays, which have a special mode of origin connected with pneumatolysis, the alkali-content shown in analyses of ordinary clay-rocks proves that kaolin is a constituent of minor importance. It may be suggested that, when it is present, it comes rather from albite than from orthoclase, since the low ratio of soda to potash in most argillaceous rocks shows that soda is to a greater extent than potash removed in solution. None the less we shall see that finely granular albite is present in many sediments of this class, while orthoclase seems to be always destroyed. However this may be, it is certain that the excessively fine flaky substance which makes a large part of all ordinary clay-rocks is of a micaceous nature. Since even the well-crystallized white micas present considerable difficulty to the systematic mineralogist, the constitution of minute flakes which cannot be isolated for analysis remains still more problematical. If we are justified in distinguishing two ideal molecules:



then the ratio $K_2O : Al_2O_3$, given by the bulk-analyses of average argillaceous sediments points decidedly to a phengitic composition.¹ The study of clays still in a plastic condition is complicated by the fact that some part of their substance is in the colloid state. This,

¹ See also analyses of 'sericite,' Niggli, *Schw. Min. Pet. Mitt.*, 1933, p. 84.

however, is only a temporary circumstance, and the rocks which suffer metamorphism may be supposed made up of definite, if sometimes imperfectly known, minerals.

Under certain physical conditions, of which a tropical climate is one, not only the feldspars but all other silicate compounds may be totally decomposed, the silica liberated passing into solution together with the whole of the alkalis, lime and magnesia. The alumina and iron remain as hydroxides, at first largely in the colloid state. With them are mingled quartz-grains, if the rock was a quartzose one, and rutile. Such deposits (laterites) represent the extreme result of the chemical degradation of silicate-rocks. According to the nature of those parent rocks, they may be almost purely aluminous (bauxite) or highly ferruginous (lithomarge). There are also accumulations of iron-oxide, normally in a hydrated form, due to direct deposition by the agency of bacteria, and these may have an admixture of siliceous and other impurities. These peculiar types of deposit, including also the kaolin-clays, will require separate treatment in the sequel. The more ordinary argillaceous sediments, notwithstanding a considerable variety of composition, can be dealt with collectively.

In the usual and less drastic course of decomposition only part of the lime, magnesia, alkalis, and silica is carried off in solution, to reappear elsewhere as limestones, salt-deposits, and cherts. Their loss, however, is enough to raise notably the proportion of the alumina which remains, and *richness in alumina* is accordingly the salient chemical characteristic of argillaceous sediments as a class. Other noteworthy features are the poverty in lime (in deposits not distinctly calcareous) and the strong preponderance of potash over soda.

In the destructive chemical changes which have been noted we see a partial breaking down (and even in laterization a complete breaking down) of higher silicate compounds to form silicates of lower type and non-silicates, the process often involving hydration or peroxidation or carbonation. Broadly we may recognize a readjustment to atmospheric conditions, i.e. to low temperature and unlimited access of water and the atmospheric gases. From the standpoint of energy-content the reactions involved are *exothermic*, and the quantity of heat evolved and dissipated in the complete chemical degradation of a crystalline rock is very great. The chemical changes in thermal metamorphism are essentially *endothermic*. Besides dehydration, reduction of peroxides, and elimination of carbon dioxide, there is in most of the reactions to be noted below a building up of higher types of silicates from lower, or of silicates from non-silicates, with the aid of the detrital quartz present. To this extent rising temperature

brings about a reversal of the changes which we have enumerated as proceeding at low temperatures. It is evident, however, having regard to the bulk-composition of argillaceous deposits, that the new minerals produced can correspond only partially with those of igneous rocks. In particular, we must expect to meet some silicates notably rich in alumina.

One other point is to be emphasized. Almost all the constituents of an argillaceous sediment result from chemical reactions completed at low temperatures. They exist as very minute particles, intimately commingled with one another and in presence of an abundant solvent. It may be assumed that under these favourable conditions a near approach to true chemical equilibrium has been attained, an assumption seldom to be justified in other rocks of composite origin. This being so, metamorphism *starts from equilibrium*; so that there is from the beginning a gradual readjustment in response to rising temperature, and the earlier stages exhibit here a clearer gradation than is to be recognized in any other class of rocks. Especially is this noteworthy in contrast with the case of those partially calcareous sediments which are excluded from present consideration, and will be treated in a later chapter.

LOWER GRADES OF METAMORPHISM IN ARGILLACEOUS SEDIMENTS

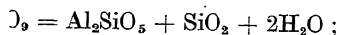
The earliest effects of rising temperature are felt by some of the minor and non-essential constituents of the sediment. Many black shales contain a noteworthy quantity of organic matter, and this is quickly affected by heating. Under a low pressure it may be wholly expelled, but more commonly it is reduced to graphite. The minute black particles have a strong tendency to gather into clots and patches, and one type of 'spotted' structure, common in the lowest grade of metamorphism is due to this aggregation of the dark pigment of the rock (Fig. 1. A). In some other black shales the finely divided dark matter is limonite and this is reduced to granules or minute octahedra of magnetite. In cleaved slates the iron-oxide is usually in the form of haematite, and this too is reduced to magnetite. The minute rutile needles, so abundant in many argillaceous sediments, give place to rather larger and stouter crystals. It is safe to assert also that, if any colloid matter still existed in the original sediment, it becomes reconstituted at a very early stage.

At a somewhat higher temperature the general body of the rock is to be affected. The process begins, as has been said, by temperature solution initiated at many isolated points throughout the mass (p. 15). If it go no farther, there will result a 'spotted slate' of the

type already described. Such rocks have been styled Knotenschiefer, Fleckschiefer, and Fruchtschiefer, names which, however, have been applied also to spotted structures of a different nature. If, on the other hand, as we now suppose, solution is duly followed by recrystallization, and the process spreads gradually through the mass of the rock, we reach a definite landmark of metamorphism in the production of one or more new minerals.

Very often the first important new product is *biotite*, and this mineral is seldom absent from metamorphosed argillaceous sediments in most succeeding grades. Although it is not possible to write down a precise equation representing the reaction, it is clear that the biotite is formed from the chlorite, 'sericite', iron-ore, and rutile of the original sediment. If much of the iron-ore enters, some free silica must be taken up too, and we see that practically all the constituents of the rock are already involved at this early stage. Of the exact composition of the biotite produced in thermal metamorphism we possess scarcely any knowledge. In the only recorded analysis¹ of such a mica the molecular ratio $K_2O : Al_2O_3$ is 0.50, which suggests that the sericite was of a phengitic composition and the chlorite of a kind poor in alumina. In the same analysis the ratio $FeO : MgO$ is 1.54, and, judged by its deep colour, the biotite of metamorphosed rocks in general is notably ferriferous. At its first appearance this mineral is in numerous very small elements, shapeless or sometimes rounded, but it soon develops the characteristic flakes, which may have either the criss-cross or the parallel arrangement (Fig. 3, above). Relatively large flakes with a poeciloblastic structure are not uncommon (Fig. 4, A).

In sediments containing any noteworthy amount of kaolin (or possibly of bauxite or gibbsite) biotite is not the first new mineral to appear, but is preceded by one of the distinctively aluminous silicates *andalusite* and *cordierite*, or by both together. Andalusite comes simply from the decomposition of kaolin :



but in the more chloritic sediments the ferro-magnesian mineral cordierite forms instead, and is in fact the commoner of the two. Unlike the nascent biotite, these aluminous silicates figure from the first as individuals of relatively large dimensions. The formation of such large crystals in a low grade, and in a matrix which is still practically unchanged, is connected with their composition and their capacity for enclosing an unusual amount of foreign matter. The

¹ Lang, *Nyt. Mag. Nat.*, vol. xxx (1886), p. 318 (Oslo district).

growth of isolated crystals in a solid rock is resisted only in so far as the rock-substance cannot be either incorporated in the crystals or enveloped by them. If the bulk composition were identical with that of the growing crystals, there would be no resistance, and the actual conditions are favourable in proportion as that ideal case is approached. The crowded minute inclusions are at this early stage merely the undigested part of the rock-substance, that residuum which could not be incorporated in the crystals themselves. At first both minerals have rounded or oval shapes. Andalusite, capable of exerting a

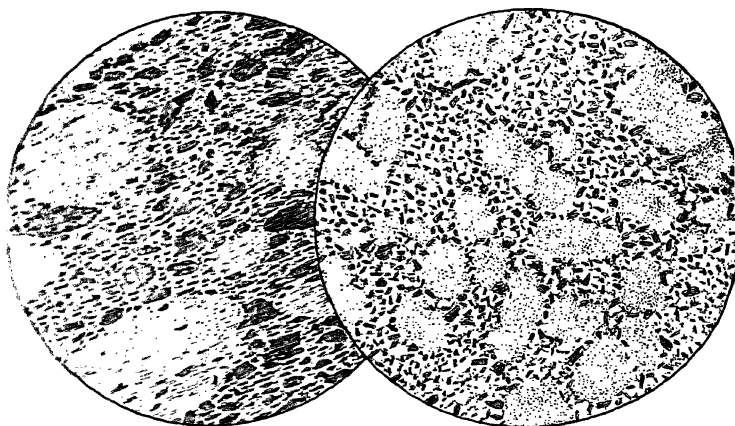


FIG. 9.—METAMORPHOSED ARGILLACEOUS ROCKS WITH ALUMINOUS SILICATES;
× 25.

minerals are seen as oval spots, containing abundant minute inclusions but are free from the biotite developed in the general matrix.

- A. Skiddaw Slates, Glenderamackin Valley, Cumberland; with large andalusites.
- B. Conistone Flags, near the Shap granite, Westmorland; with numerous round

: force of crystallization, speedily acquires crystal outline, always that of the simple prism, and pushes aside its enclosed foreign matter into the familiar chialstolite pattern. The feebler cordierite very seldom attains to any crystal shape, and is unable to clear itself from inclusions

It is not to be supposed that these aluminous silicates are formed only when kaolin was present. They are also produced jointly with biotite by reactions involving 'sericite', chlorite, and iron-ore. In this case they come in at a rather later stage, and may continue to form, together with biotite, until some part of the requisite material

is exhausted. As before, their first appearance is in round grains. These are conspicuous by contrast, being relatively free from the biotite-flakes abundantly developed in the rest of the rock, and they thus characterize still another type of 'spotted slate' (Fig. 9). The andalusite makes well-defined crystals, clear except for the chialstolite cross (Fig. 7), and at a later stage this also disappears (Fig. 10). The shapeless grains of cordierite still carry abundant inclusions, but these have now become converted to recognizable minerals, such as biotite and quartz (Fig. 11, B). The cordierite at this stage often shows its

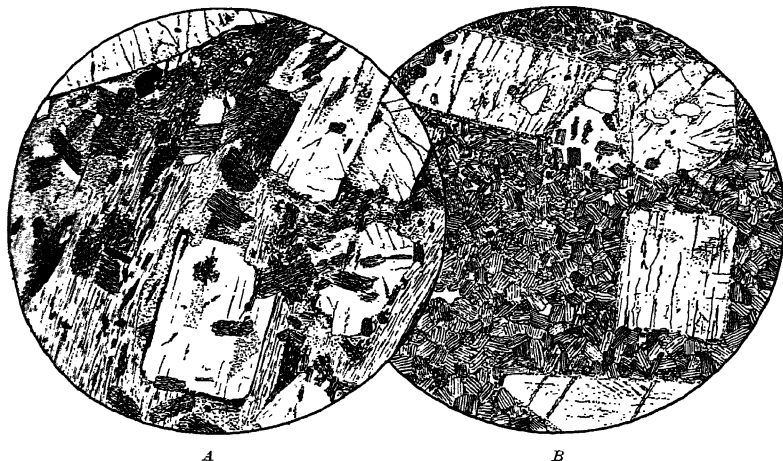


FIG. 10.—ANDALUSITE-BEARING ROCKS; $\times 25$.

A. Andalusite-Mica-schist, Killiney, near the Dublin granite. Besides biotite, this rock contains abundant large flakes of muscovite with parallel disposition.

B. Andalusite-Biotite-Hornfels, Perran Sands, near the Cligga Head granite, Cornwall. The biotite illustrates the typical decussate structure.

characteristic polysynthetic twinning. It is to be observed that this mineral is not merely a magnesian but a ferro-magnesian silicate, having the general formula $(\text{Mg,Fe})_2\text{Al}_4\text{Si}_5\text{O}_{18}$. The molecular ratio $\text{FeO} : \text{MgO}$ is sometimes higher than unity, and has probably no limit. The highly ferriferous variety imparts to a rock of which it makes the chief bulk a deep violet colour, with an unmistakable resinous lustre. In a thin slice it is seen making a general mosaic in which the other constituents are embedded, and has often a distinctly bluish tint.

MEDIUM GRADES OF METAMORPHISM IN ARGILLACEOUS SEDIMENTS

At the stage now reached nothing of the original material remains unchanged. What has not been used to make new minerals has

ARGILLACEOUS SEDIMENTS

recrystallized. The remaining quartz, according to its greater or less amount, figures in a fine-grained mosaic or appears as new granules enclosed in cordierite. If white mica is left, it is in new flakes, much larger than the original minute scales of 'sericite', and it may be assumed to have now the composition of muscovite, allowing for some replacement of potash by soda. If we exclude rocks at granite-contacts, where pneumatolysis may be suspected, muscovite is a much less common mineral among the products of thermal metamorphism than in the crystalline schists. Of other minerals, some magnetite

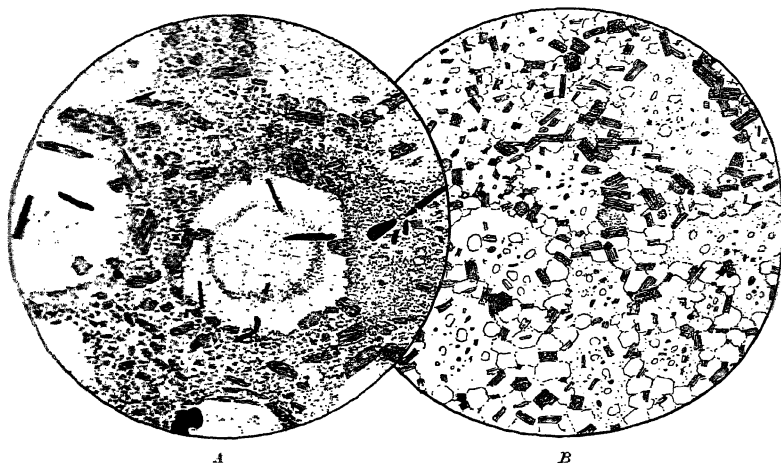


FIG. 11.—CORDIERITE-BIOTITE-HORNFELS; $\times 25$.

- A. Metamorphosed Skiddaw Slates, Bowseale Tarn. The cordierite crystals here are usually well developed, one basal section showing the hexagonal outline and also the arrangement of inclusions (p. 44). The opaque mineral is ilmenite.
- B. Metamorphosed Culm, Leusdon Common, near the Dartmoor granite. This is at a higher grade of metamorphism. The cordierite contains recognizable inclusions of biotite and quartz.

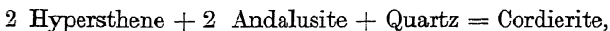
usually remains, though in much-reduced quantity. Besides contributing to the making of biotite and cordierite, it has sometimes reacted with rutile to produce flakes of ilmenite (Fig. 11, A). Most of the original rutile has gone into biotite, but a few crystals may be left even in an advanced grade of metamorphism. The other two forms of titania are also known, but in this mode of occurrence are decidedly rarities and perhaps anomalies. Brookite¹ has

¹ *Neu. Jb. Min.*, 1892, vol. i, pp. 159-60; *Tscherm. Min. Petr.* xiv (1893), p. 314 (Elbe Valley).

recorded in a comparatively low grade of metamorphism, and anatase¹ in a more advanced grade. They do not take the place of rutile at any determinate stage, but occur capriciously and sporadically, and it is probable that both minerals are here merely metastable forms.

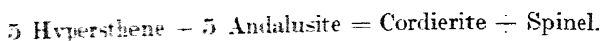
That a rock is totally reconstituted does not imply finality, for, with further rise of temperature, new reactions will come into play, giving rise to new minerals. In following the further course of metamorphism, we have to observe that it takes one line or another in accordance with initial differences of composition. Much depends upon the ratio of alumina to magnesia, and therefore upon the relative proportions of the sericitic and chloritic constituents in the original sediment. It is mainly from these that the new minerals have been formed in the earlier stages of metamorphism already discussed, and which of the two is first exhausted is now the important criterion. An excess of chlorite on the one hand or of white mica on the other will lead to different results in the higher grades of metamorphism.

Suppose, first, that there is an excess of chlorite after all the white mica has disappeared. This chlorite does not remain unchanged, or merely recrystallized, through higher grades of metamorphism, but takes part in further reactions. These are (i) conversion of any andalusite present to cordierite; (ii) if this has not disposed of all the chlorite, formation of some new ferro-magnesian silicate, either non-aluminous or at least with a ratio $RO : R_2O_3$ greater than in cordierite and biotite; (iii) possible liberation of some iron in the form of magnetite. The new ferro-magnesian silicates which satisfy the conditions are rhombic pyroxene and a garnet of the almandine-pyropessartine series, and the mineral usually produced is *hypersthene*. Although it has been recorded as a normal product of thermal metamorphism in the Oslo district, the Harz, the Comrie district, and elsewhere, it is not a mineral of very common occurrence at this stage. The reason is that sediments very rich in chlorite are usually more or less calcareous, and then give rise to hornblende instead of a rhombic pyroxene. The formation of hypersthene in high grade hornfelses has, as will be shown, a different significance. At its first appearance this mineral makes slender prisms or small crystal-grains and in no great abundance (Fig. 12, A). Its associates are cordierite, biotite, quartz, and magnetite, muscovite and orthoclase being obviously excluded. Andalusite, too, is excluded, in virtue of the relation:



¹ Hutchings, *cit.* Harker and Marr, *Quart. Journ. Geol. Soc.*, vol. xlvii (1891), p. 318 (Shap granite aureole).

or, if silica be in defect :



these reactions ensuring that hypersthene does not form until any andalusite present has become replaced by cordierite.

The place of hypersthene (or rather of hypersthene and cordierite) is sometimes taken by a red *garnet*, and the status of this mineral as a product of simple thermal metamorphism calls for some discussion. Although it is abundant in the inner aureoles of the Skiddaw, Foxdale,

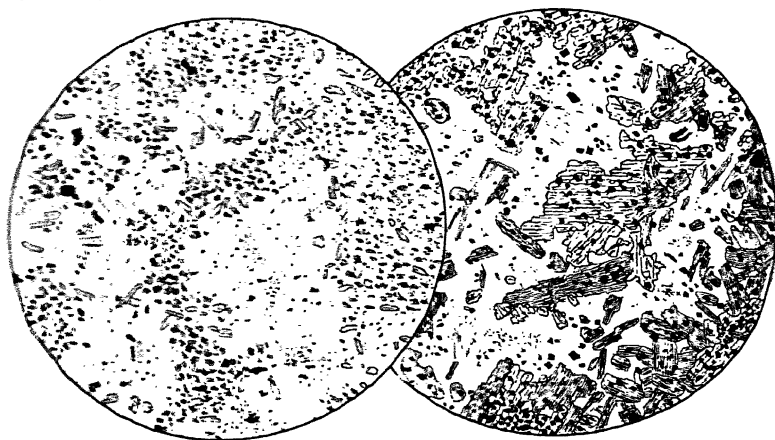


FIG. 12.—HYPERSTHENE-BIOTITE-CORDIERITE-HORNFELS, from the aureole of the Carn Chois diorite, near Comrie, Perthshire ; $\times 23$.

A. Little prisms of hypersthene, minute scales of biotite, granules of magnetite, and fine dust or flocks of graphite are set in a matrix of cordierite-mosaic, without quartz.

B. Here, in a higher grade of metamorphism, the hypersthene and biotite make crystals of conspicuous size. The abundant little nearly opaque granules are octahedra of pleonaste, and mark this rock as one deficient in silica (see below).

Galloway, and Leinster granites, and is recorded from some areas, the occurrence of garnet (other than a lime-garnet) in such connexion is at first sight anomalous. We shall see that the red garnet, approaching almandine in composition, is a highly mineral of regional metamorphism ; but, when the mica-schists of the Highlands enter the aureole of one of the 'Newer Granites', the garnet is destroyed. This marks almandine as a mineral proper to metamorphism only under stress-conditions. It is important therefore to note that such analyses as we possess of garnets from thermally metamorphosed non-calcareous sediments indicate in general, almandine, but a mixed garnet containing a notable proportion

of spessartine. Sollas¹ found 18.55 per cent of manganous oxide in a garnet from Carrickmines, Co. Dublin. Tilley² found 14.88 per cent. in the New Galloway garnet and 6.02 in that of Grainsgill (Skiddaw granite aureole). We may infer with some confidence that the formation of garnet in thermal metamorphism is favoured by the presence of a certain amount of manganese in the rock, and that the garnet produced has then a composition between almandine and spessartine. It is perhaps significant that spessartine, unlike almandine and pyrope, can be reproduced in the laboratory from its constituent oxides. Goldschmidt's researches at Stavanger prove that rocks with a very small content of manganese may yield a richly manganiferous garnet.

It cannot, however, be ruled therefore that the presence of manganese (or lime) is absolutely essential. A garnet from Gadernheim in the Odenwald, in the aureole of an intrusion of hornblende-gabbro, was found by Klemm³ to be a nearly pure almandine, with only 1.90 per cent of manganous oxide and 1.45 to 1.93 of lime. Here we have to do undoubtedly with a very deep-seated intrusion, and we may conjecture that under a sufficiently great pressure even almandine may form freely. Another instance is the well-known garnet of Botallack, in the aureole of the Land's End granite, Cornwall.⁴

The garnet makes idioblastic crystals with the usual dodecahedral habit. There may be a crowd of minute crystals enclosed in biotite or cordierite or quartz (Fig. 13, *C*); but more commonly garnet is from the first of conspicuous size (Fig. 3, *B*) and still more so in the highest grades of metamorphism (Fig. 17, *B*).

In argillaceous rocks originally poor in chlorite there is more white mica than can be consumed in the early reactions which yield biotite, etc., and the excess appears as recrystallized muscovite. It seems that under certain conditions this mineral may survive into an advanced grade, and Tilley⁵ has suggested that this is the normal course in presence of a sufficiency of water. It should be remarked, however, that the abundant white mica often found in the neighbourhood of a granite-contact is certainly a pneumatolytic product. In the general case it appears that, with advancing metamorphism, muscovite dwindles and disappears, and *orthoclase* is formed in its place.

If we assume the mica to have the ideal muscovite composition,

¹ *Sci. Proc. Roy. Dubl. Soc.* (2), vol. vii (1891), p. 49.

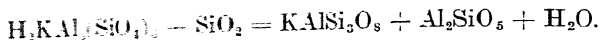
² *Min. Mag.*, vol. xxi (1926), p. 49.

³ *Notizbl. Ver. Erdk. Darmst.*, v. Folge, Heft 4 (1919), p. 20.

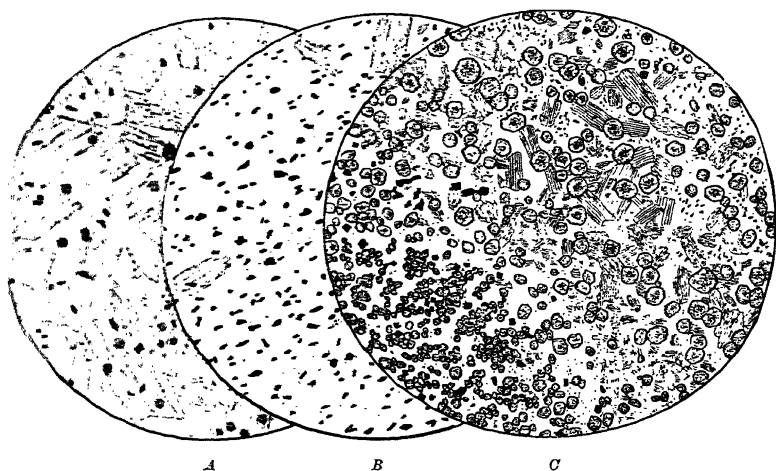
⁴ Alderman, *Min. Mag.*, vol. xxiv (1935), pp. 42-3.

⁵ *Min. Mag.*, vol. xxi (1926), p. 49.

and conceive it as derived originally from orthoclase, it is clear that in the process the felspar must have parted with two-thirds of its alkali and silica, besides taking up water. The alkali so removed being lost irretrievably, the mica can be reconverted to felspar only by the abstraction of two-thirds of its alumina. In presence of free silica the alumina so liberated goes to make andalusite:



Andalusite thus produced as a by-product of the formation of felspar and thus a different significance from that generated in lower grades



13.—BIOTITE-CORDIERITE-HORNFELS, from the metamorphosed Skiddaw Slates of the Caldew Valley, Cumberland; $\times 25$.

and *B* represent different bands in the same thin slice, one rich in biotite with the [haloes, the other mainly of cordierite with many little crystals of

C is a garnetiferous variety, also banded. One part shows a crowd of minute garnets set in quartz; another part is mainly of cordierite and biotite with rather larger garnets.

of metamorphism. Since the white mica of these rocks constantly contains a certain proportion of soda, some albite is produced with the orthoclase. If, however, the ratio of soda to potash is not higher than 1 : 4, the albite may be concealed by solid solution in the orthoclase.

At its first appearance, in a medium grade of metamorphism, the alkali-felspar figures as minute granules, which rarely show twinning, and, when involved in a fine mosaic with quartz, may easily be overlooked. A useful criterion is that against cordierite quartz is idioblastic orthoclase xenoblastic. Albite can often be identified by its low

refractive index. When albite-oligoclase or oligoclase occurs instead, this is of course due to some small content of lime in the original sediment. With advancing metamorphism the felspar, like other minerals, is usually in larger elements, and then often shows the characteristic twinning. In the highest grade of metamorphism felspar sometimes becomes abundant. Much of it then is newly formed, and comes from the breaking up of biotite, a matter which calls for more particular notice.

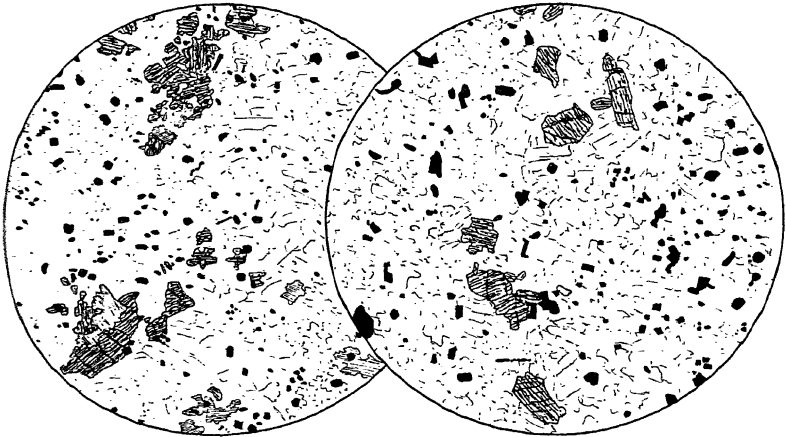


FIG. 14.—HYPERSTHENE-ORTHOCLASE-CORDIERITE-HORNFELS, from the inner aureole of the Carn Chois diorite, near Comrie, Perthshire; $\times 23$.

A. Some biotite is present, but is corroded and in process of destruction.

B. Here biotite is wanting, and orthoclase is more abundant. A band down the middle of the field is composed almost wholly of hypersthene and orthoclase.

HIGHER GRADES OF METAMORPHISM ARGILLACEOUS SEDIMENTS

The dark mica more often than the white maintains its stability to the last, and it may be very abundant in highly metamorphosed rocks (Figs. 2, A; 3, B; 10; etc.). Especially is this found in the inner aureole of one of the more acid granites and in xenoliths enclosed in such a rock, the magma of which was capable of furnishing an ample supply of water and perhaps of other volatile bodies. Under other conditions it is often very evident that, as we pass to the highest grade of metamorphism, biotite dwindles and disappears. The potassic part goes to make orthoclase, with some aluminous silicate, while the ferro-magnesian part gives rise to hypersthene or possibly to garnet. This is the most usual origin of hypersthene in thermal

metamorphism. When that mineral is produced at an earlier stage, as we have seen, its existence is incompatible with the presence of orthoclase. In the rocks now in question hypersthene and orthoclase are associated in abundance, together with cordierite. These and a little magnetite are often the only constituents. If biotite is present, it is seen to be in process of destruction. Characteristic examples occur near the diorite contact in the Comrie district (Fig. 14).

The weak mineral cordierite has, at these high temperatures, an enhanced force of crystallization. It shows idioblastic outline, though

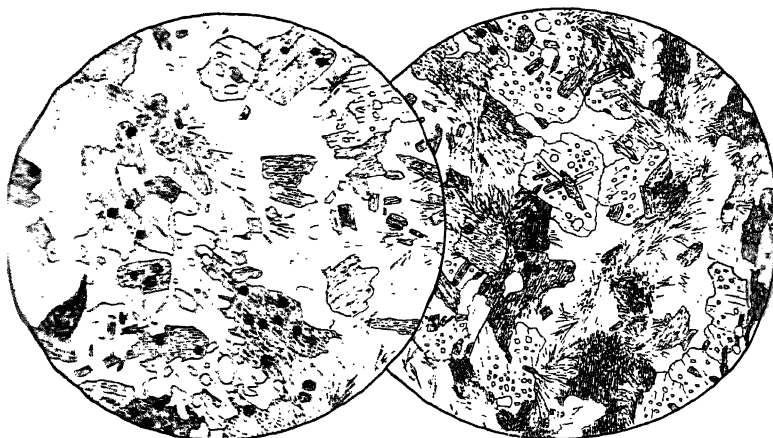


FIG. 15.—SILLIMANITE-CORDIERITE-GNEISS, M'Phatlees Location, Northern Transvaal; $\times 23$.

From the aureole of the Bushveld plutonic complex (Hall, *Tsch. Min. Pet.*, vol. xxviii (1909), p. 135). The sillimanite, in closely packed bundles of fine needles, forms at the expense of the biotite. Cordierite, enclosing quartz-granules, is conspicuous (over-emphasized in the drawing). Other constituents of the rock are orthoclase, quartz, some andalusite and muscovite, and minute zircons, causing dark halos in the biotite.

against the still weaker orthoclase. The aluminous silicate which is formed together with orthoclase in this highest grade is not andalusite but *sillimanite*, which thus comes to have a critical significance. Its relation to the biotite from which it is derived is sometimes apparent (Fig. 15); but doubtless sillimanite may arise also in other ways, and in particular from the inversion of andalusite formed at some earlier stage. There is no evidence that such inversion effect at a determinate temperature, and indeed andalusite is sometimes found in company with the higher and doubtless stable

form. Sillimanite occurs in slender prisms¹ of fine needles, often crowded together with a sub-parallel or sheaf-like arrangement (Figs. 15, 17, *B*).

We have seen that, in the reactions by which the aluminous silicate-minerals are built up, there is in almost every case a taking up of silica; and we have hitherto assumed a sufficiency of silica, originally present in the form of detrital quartz, to satisfy all requirements. This condition, however, is not always realized; and, when the free silica is exhausted before the end is reached, metamorphism in the

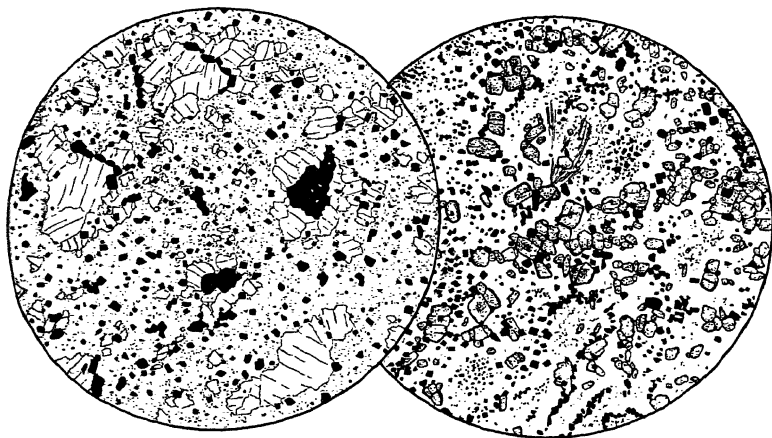


FIG. 16.—HIGH-GRADE TYPES OF HORNFELS POOR IN SILICA, from the aureole of the Carn Chois diorite, near Comrie, Perthshire; $\times 23$.

A. Pleonaste-Orthoclase-Cordierite Hornfels. The nearly opaque octahedra are of a spinel near pleonaste; the clear crystals showing cleavage are of orthoclase; the rest is a granular aggregate of cordierite.

B. Corundum-Cordierite Hornfels. The conspicuous crystals showing in relief are of corundum; the opaque mineral is pleonaste; and the other constituents are alkali-feldspars and cordierite. This is the rock analysed by Tilley, *Quart. Journ. Geol. Soc.*, vol. lxxx (1924), p. 46.

highest grades must necessarily follow in part different lines. Owing to the deficiency of silica, cordierite comes to be represented in part by a spinel mineral, and andalusite and sillimanite give place partly or wholly to corundum. The spinellid occurs in very numerous little octahedra, of so deep a green as to be barely translucent in thin slices (Figs. 12 *B*; 16). It may be set down as a *pleonaste* approaching hercynite in composition. It is probably more highly ferriferous than

¹ It is one of the few minerals of metamorphism in which the common habit does not conform with the principal cleavage, which is pinacoidal.

ARGILLACEOUS SEDIMENTS

which it represents and accompanies, and with this we may correlate the usual absence of magnetite in rocks of this type. The *corundum* is in crystals usually of no great size (Fig. 16, *B*), the common habit being that of imperfect hexagonal discs, though the 'barrel' shape, with elongation along the vertical axis, is also found. A bluish tint is often perceptible in thin slices and sometimes a strong blue colour (sapphire), e.g., near Cape Cornwall.

Rocks carrying corundum are, of course, normally devoid of quartz, but it is easy to find apparent exceptions to the general rule. We

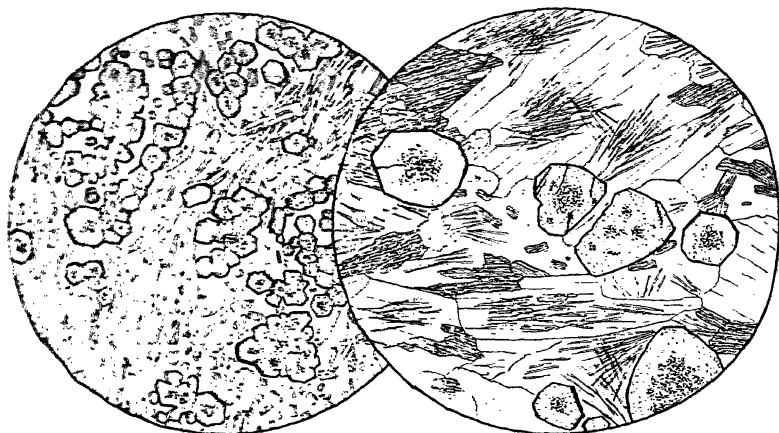


FIG. 17.—HIGHLY METAMORPHOSED ARGILLACEOUS SEDIMENTS of Silurian age bordering the Cairnsmore of Fleet granite at New Galloway; $\times 25$.

A. Garnet-Gneiss. This has been a rather siliceous shale, and contains abundant quartz. The other chief constituents are garnet, muscovite, and biotite.

B. Sillimanite-Gneiss: a very coarse-grained rock consisting of garnet, two micas, feldspar, with abundant needles of sillimanite, mostly enclosed in the

may even see in a rock-slice a crystal of corundum or pleonaste very near to a grain of quartz, though not in contact with it. The original sediment consisted of more siliceous and less siliceous seams, and the very narrow amplitude of diffusion possible in metamorphism has imposed a corresponding check upon chemical reactions. In truth the 'system' for which Goldschmidt's adaptation of the Phase Rule may hold good (p. 4) is not the rock as a whole, but merely any portion of it small enough to be comprised within the sphere of free diffusion.

The most highly metamorphosed rocks, quartz-bearing or not, on often, though by no means universally, a decidedly coarse

texture. The principal constituent minerals—cordierite, micas, garnet, felspars, quartz, in different types—tend to relatively large dimensions, though some other minerals, such as sillimanite and the spinellids, are still in only small crystals. While the general type of structure remains the same, the term 'hornfels' is not appropriate to these coarse-grained rocks, and they are generally designated by the name (itself vague and unsatisfactory) of 'gneiss'. To this is added some prefix, either of the most abundant mineral, as *cordierite-gneiss* (Fig. 27), or the mineral most distinctive and significant, as *garnet-gneiss* (Fig. 17, *A*), or *sillimanite-gneiss* (Fig. 17, *B*). Very characteristic is a more or less pronounced banded structure, evident in the field or under the microscope. This has been determined by original differences of composition, but accentuated by a certain amount of segregation, rendered possible by the enlarged amplitude of diffusion at the highest temperatures of metamorphism (p. 19).

In strong contrast with these coarse-textured types is another, rather exceptional, class of products, which equally represent a very high grade of metamorphism. These are the *vitrified shales and slates* already referred to (p. 27). They consist essentially of a brown glass; but the solution of the original substance has not always been complete, and residual elements are often present, especially corroded granules of quartz. In addition there has always been a certain amount of new crystallization, yielding minute but perfectly formed crystals of cordierite, sillimanite, pleonaste, magnetite, etc. Locally fused phyllites showing these characters are found bordering basic and ultrabasic dykes in the Highlands of Argyllshire.¹

¹ *Geology of Oban and Dalmally (Mem. Geol. Sur Scot., 1908), pp. 129-32, and Geology of Colonsay, etc. (1911), pp. 94-5.*

CHAPTER V

THERMAL METAMORPHISM OF NON-CALCAREOUS SEDIMENTS (*continued*)

Successive Zones of Thermal Metamorphism—Thermal Metamorphism of Aluminous and Ferruginous Deposits—Constitution of Arenaceous Sediments—Thermal Metamorphism of Pure Arenaceous Sediments—Thermal Metamorphism of More Impure Arenaceous Sediments.

SUCCESSIVE ZONES OF THERMAL METAMORPHISM

ON an earlier page reference has been made to the possibility of dividing a metamorphic aureole into successive *zones*, marked by the coming in of different new minerals generated with the advance of metamorphism (p. 24). In the light of what we have now learnt, it is to give an answer to the question there posed. In any given sufficiently well exposed, careful study will enable us to recognize certain definite landmarks of the kind sought; but these are likely to be different in different cases, and no complete scheme of general application can be laid down. Among what we roughly group together as ordinary argillaceous sediments there is in fact a diversity of composition which leads in thermal metamorphism to quite different mineralogical developments.

The most constant indices are, in a low grade, the production of biotite; in a middle grade, the first formation of orthoclase at the expense of muscovite, or alternatively the appearance of hypersthene or garnet; and, if a very high grade is reached, the coming in of sillimanite or corundum. Even here, as we have seen, the breaking up of muscovite to yield orthoclase may be indefinitely postponed, and this owing, not to anything in the initial composition of the rock, but to the proximity of a granite-contact. A like remark applies to the possible breaking up of biotite in a much more advanced grade. The most characteristic products of metamorphism, cordierite and andalusite, may make their first appearance at an earlier or later grade and have therefore no precise value as indices.

METAMORPHISM OF ALUMINOUS AND FERRUGINOUS DEPOSITS

We go on to consider briefly the effects of thermal metamorphism in those highly aluminous and ferruginous deposits which stand apart

from more ordinary argillaceous sediments. A pure kaolin clay can yield only an aggregate of andalusite and quartz (p. 49), or in a very high grade sillimanite and quartz. If such rocks are to be found, they must be of rare occurrence. A deposit consisting simply of aluminium hydrate merely suffers dehydration when metamorphosed. Gibbsite ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$) and bauxite ($\text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$) are thus reduced to corundum, giving the rock known as emery, though the best-known occurrences of emery are related to metamorphism of the type. Often there is some admixture of flaky diaspore

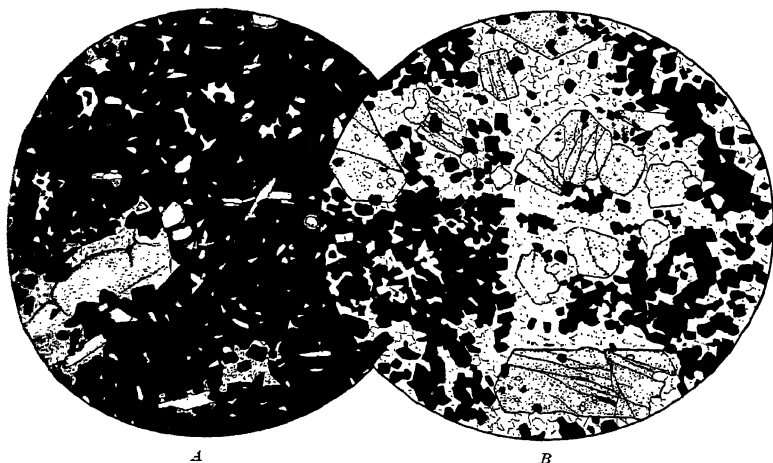


FIG. 18.—METAMORPHOSED BOLE, near Kilchoan, Ardnamurchan; $\times 23$.

A. Essentially of hercynite and corundum, the latter encrusted in places with finely flaky diaspore. A little clear anorthite occurs interstitially.

B. Porphyroblasts of corundum and little octahedra of hercynite are embedded in a granular aggregate of anorthite.

($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$), either from incomplete dehydration or by subsequent alteration of corundum. Bauxitic deposits, however, are usually more or less ferruginous, and give rise then to an iron-spinel (hercynite) in addition to corundum. If there was any calcareous admixture in the original deposit, this is represented by anorthite. Examples of these rather peculiar types of rocks have not often been recorded. Klemm¹ has described an interesting occurrence in the contact-aureole of a diorite intrusion in the Odenwald. The emery here consists of corundum, deep-green spinel, and iron-ore. It makes part of a banded series with various types of hornfels rich in cordierite

¹ *Notizbl. Ver. Erdk. Darmstadt*, v. Folge, Heft 1 (1916), pp. 1-41.

and sometimes containing corundum. In Ardnamurchan¹ one of the red bands of bole, due to destructive contemporaneous weathering of the Tertiary basalt lavas, has been metamorphosed by a later intrusion of gabbro. It is converted to an aggregate of blue corundum and nearly opaque hercynite with often abundant anorthite (Fig. 18). At the same place another variety, which has been mainly ferruginous in composition, is represented by a rock essentially of magnetite.

When a deposit of hydrated ferric oxide undergoes metamorphism, there is a reduction first of limonite to haematite and then of haematite

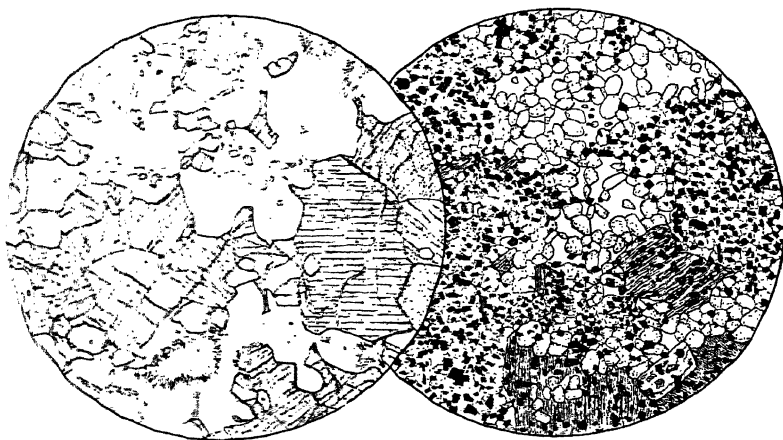


FIG. 19.—

IMPURE HAEMATITE ORES, Riekensglück,
Harz; $\times 23$.

A. Fayalite-Quartz-rock. Reaction between the two minerals has produced in places the iron-amphibole grunerite, partly in radiating fibres, partly in compact crystals.
B. Fayalite-Pleonaste-rock, with garnet, biotite, and cordierite.

to magnetite. The latter process may be incomplete, and so, besides magnetite-ores, we have others composed of magnetite and in varying proportions. Aluminous and other impurities may give rise to other minerals in addition. In the contact-aureole of the Rostrenan granite in Brittany, Barrois² records impure limonite, converted to a mixture of magnetite and the iron-chlorite chamosite. So too the presence of lime gives rise to andradite, as in some localities in the Harz³ and elsewhere.

¹ *The Geology of Ardnamurchan* (*Mem. Geol. Sur. Scot.*, 1930), pp. 233-4.
Soc. Geol. Nord (2), vol. xii (1885), p. 78.
Deuts. Geol. Ges., vol. xxix (1877), p. 206.

In general any free silica which may be present recrystallizes side by side with the magnetite without any mutual reaction, but there are interesting exceptions. Ramdohr¹ has described the metamorphism of the haematite deposits of the Harz in the aureole of the Brocken granite. The original ores were in varying degree siliceous, and usually magnetite and quartz have crystallized together. Under some conditions, however, there has been a reaction, giving rise to fayalite, and sometimes a further reaction converting the orthosilicate to the metasilicate grunerite (Fig. 19, *A*). With aluminous and other impurities present in the ore, fayalite comes to be accompanied by pleonaste, cordierite, garnet, biotite, etc. (Fig. 19, *B*).

CONSTITUTION OF ARENACEOUS SEDIMENTS

The arenaceous sediments, representing the coarser detritus from the erosion of land-surfaces, are derived in the main from the mechanical disintegration, not chemical degradation, of the parent rock-masses. These may be conceived as crystalline rocks of various kinds, including crystalline schists. In so far as a sand may come from the breaking down of older sandstones, this merely introduces an intermediate step between the deposit and its ultimate source. Sand-grains consist accordingly of those minerals which make up the prevalent types of crystalline rocks within the drainage-basin, but *selected* with reference to their durability under atmospheric conditions.

First in importance stands quartz, which makes the bulk of most ordinary sands. With it, in much smaller quantity, muscovite has a wide distribution, being chemically indestructible under the conditions implied in erosion and transportation. Felspars, pyroxenes, hornblende, and biotite are in varying degree liable to suffer decomposition, and are consequently of less common occurrence in sands deposited under normal climatic conditions; and the most easily destructible minerals, such as olivine and nepheline, are not found. The climatic conditions here contemplated are those which must always prevail over most parts of the globe, implying a sufficiency of moisture to facilitate the usual chemical changes. In a very arid climate, and also under arctic conditions, weathering is practically in abeyance; so that a desert sand, for instance, may contain abundant fresh feldspar. This we may regard as a special case.

The distinctive minerals of crystalline schists and other metamorphosed rocks make their contribution to sands. Tourmaline and common garnet, and in a less degree cyanite and staurolite, are

¹ *Centr. f. Min.*, 1923, pp. 289-97; *Neu. Jahrb.*, Beil. Bd. lv (1927), pp. 333-92.

sufficiently stable to persist : some other minerals, such as andalusite and cordierite, have usually perished. Of interest too are the minor accessory minerals which occur as minute crystals in igneous and other crystalline rocks : zircon, rutile, anatase, apatite, and the rest. Most of these are chemically stable, and so come to have a wide distribution, in very sparing amount, in detrital sediments. They are, as a class, heavy minerals, and for this reason, despite the small size of the crystals, they figure rather in sands than in clays. The densest minerals—magnetite and ilmenite, pyrites and pyrrhotite—tend to be concentrated in particular seams of the deposit.

In all arenaceous sediments other than incoherent sands there is, in addition to the detrital grains, some cementing material, which serves to bind the grains together. This may be furnished from the substance of the grains themselves, especially by recrystallization of a small part of the quartz. In many of our Lower Palaeozoic grits the interstitial cement is of quartz enclosing chlorite, sericite, or kaolin, these being derived from the decomposition in place of grains of felspar, hornblende, and other minerals. Other common cementing substances are iron-oxide (haematite or limonite) and calcite, the last probably often introduced in solution from an extraneous source. It is to be recognized also that the ideal severance between coarser and finer detritus as laid down under water and the deposition of calcareous material on separate areas of the sea-floor are in fact only imperfectly realized. For these reasons most arenaceous sediments include, in addition to the clastic grains, some admixture of material having a different origin. Ferruginous and partly argillaceous sandstones may be treated together with those of purer constitution ; but the presence of any notable amount of carbonate so modifies the course of metamorphism, that calcareous sandstones will be more conveniently considered in another place.

THERMAL METAMORPHISM OF PURER ARENACEOUS SEDIMENTS

It is in the adventitious element present in most arenaceous rocks that the earliest effects of metamorphism are commonly to be observed. In a pure quartzose sandstone or quartzite no change is to be expected, until a temperature is reached at which a general recrystallization sets in. The only exception is the dissipation of fluid-inclusions in the quartz-grains, an effect first noted by Sorby.¹ A pure quartz-rock recrystallized in metamorphism presents a typical example of the simple mosaic structure, in which all traces of the former clastic are obliterated (Fig. 20, *A*). At the same time, any slight

¹ *Quart. Journ. Geol. Soc.*, vol. xxxvi (1880), Proc., p. 82.

original impurity betrays itself by the formation of granules or scales of some new mineral scattered through the quartz-mosaic. A chert, composed originally of cryptocrystalline silica, likewise recrystallizes to a quartzite in thermal metamorphism.

A feature of these metamorphic quartzites is their even-grained texture, connected, as we have seen, with the influence of surface-tension on solubility (p. 20). In a rock of such simple constitution size of grain may afford a rough index of the grade of metamorphism attained.

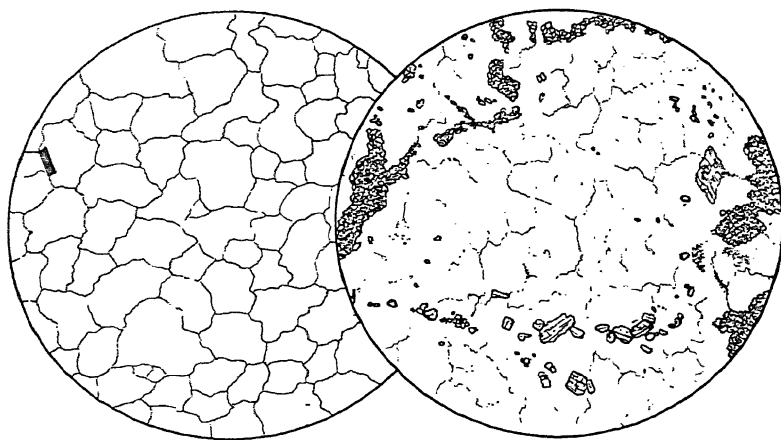


FIG. 20.—QUARTZITES ; $\times 25$.

A. Manx Grit, metamorphosed near the Foxdale granite, Isle of Man: the whole recrystallized to a simple mosaic of quartz.

B. Grit in Coniston Flags, metamorphosed near the Shap granite, Westmorland. In addition to quartz, there is some augite, formed by reaction between chlorite and calcite in the original sediment.

Increasing coarseness of texture is not, however, the only possible change in a purely quartzose rock which, already recrystallized, is subjected to further rise of temperature. The point 575°C ., which marks the inversion between the two forms of quartz, must often be passed in metamorphism of an advanced grade, and the change is one which takes effect promptly in either direction. Doubtless there are among our metamorphic quartzites not a few in which the quartz has been of the highest form, and has inverted to the lower on cooling; but the signs which mark this change in the coarser granites and pegmatites¹ will probably not be detected in ordinary quartzites.

¹ Wright and Larsen, *Amer. Journ. Sci.* (4), vol. xxvii (1909), pp. 421-47.

Another significant point on the 'geological thermometer' is 870° C., the inversion-point between quartz and tridymite. It is probable that this temperature also is sometimes attained in metamorphism of the highest grade, as in the near vicinity of an ultrabasic intrusion. It is well known that the inversion is one which proceeds with extreme reluctance, and may be indefinitely suspended. There is also the possibility that tridymite may be formed at temperatures below the theoretical inversion-point.¹ Whether the production of tridymite in high-grade metamorphism leaves any permanent trace in the cooled

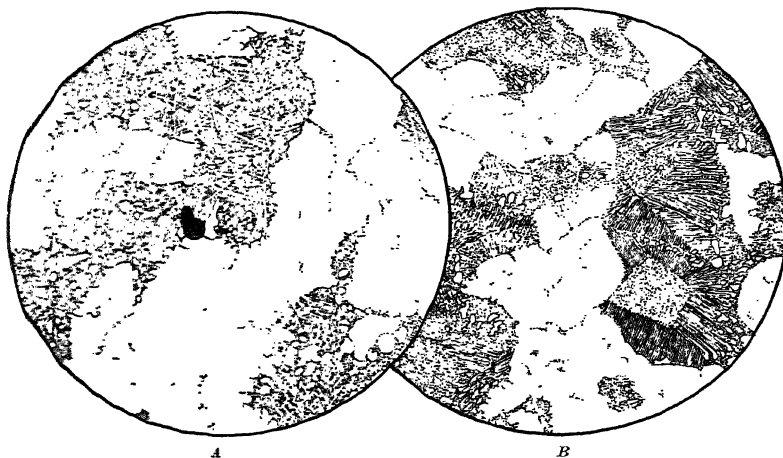


FIG. 21.—HIGHLY METAMORPHOSED FELDSPATHIC SANDSTONE, in the Torridonian bordering ultrabasic intrusions, Isle of Rum; $\times 25$.

A. The rock is wholly recrystallized, and much of the quartz has given rise to flakes of tridymite. These, embedded in feldspar, preserve their outlines, although now replaced by quartz.

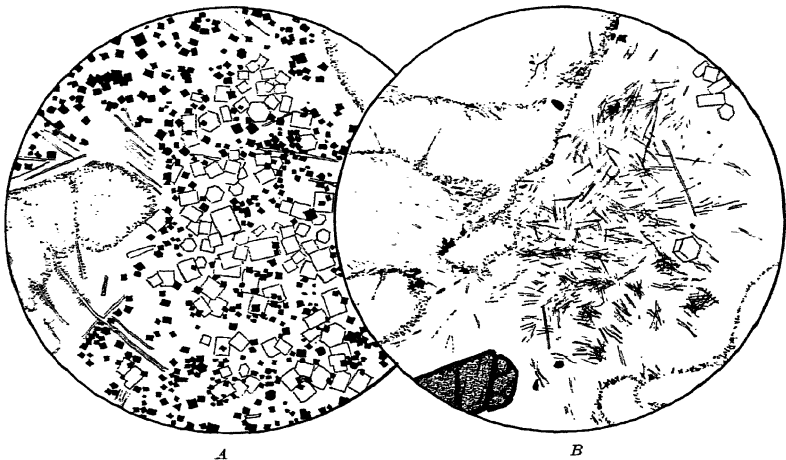
B. Here much of the recrystallized quartz has entered into delicate micrographic structures with the feldspar.

rock must depend upon the circumstances of the case. With relatively rapid cooling it is perhaps possible that the tridymite itself may be preserved as a characteristic aggregate of minute flakes, while a somewhat slower rate of cooling may yield quartz in shapes pseudomorphic after tridymite. More often, it may be, sufficiently gradual cooling in presence of a solvent will permit of a rearrangement in which such residual structure is lost.

A case more favourable for study is that of a *feldspathic sandstone*. Here the shapes of tridymite, formed in a high grade of metamorphism, are preserved by being embedded either in recrystallized

¹Cf. Larsen, *Amer. Min.*, vol. xiv (1929), p. 87.

lized felspar or in glass. The Torridon Sandstone of the North-West Highlands is composed essentially of quartz and abundant fresh felspar, mostly a red microcline. At several places in the Isle of Rum it is highly metamorphosed near intrusions of eucrite and peridotite. As in other red sandstones, the first sign of change is the disappearance of the red colour, which results from the disseminated minute scales of haematite being reduced to magnetite. Ultimately quartz and felspar are alike recrystallized. In places where all was quartz the usual mosaic structure is seen ; but where



G. 22.—VITRIFIED SANDSTONES, showing corroded relics of quartz in a colourless glass ; $\times 125$.

- A. Isle of Soay, near Skye : with minute crystals of cordierite, magnetite, and oxene.
- B. Corrary, Islay : showing cordierite and fine needles probably of mullite. A detrital crystal of zircon is fractured but not otherwise changed.

quartz was in contact with felspar, it shows a crenulated outline due to corrosion ; and there has been an abundant production of little tridymite flakes, either as a fringing growth or more widely dispersed (Fig. 21, A). These are now changed to quartz. Elsewhere recrystallizing quartz has entered into micrographic intergrowth with felspar, showing much variety of detail (Fig. 21, A, B). Indeed, except in the preponderance of quartz over felspar, some of these metamorphosed arkoses reproduce all the features of granophyres and spherulitic quartz-porphyrus.

In some occurrences of metamorphosed sandstones, comparable with those near the peridotites of Rum, but where the cooling has

been more rapid, more or less glass is produced, having the composition of a mixture of feldspar and quartz; and, embedded in this, pseudomorphs after tridymite may be preserved. A good example is the Old Red Sandstone at its contact with the Bartestree dyke, near Hereford.¹ The same thing is seen more frequently in partly fused xenoliths of sandstone enclosed in basic intrusions, such as those described by Thomas² from Mull.

It should be remarked that sandstones, no less than slates, may be more or less completely vitrified under favourable conditions, and

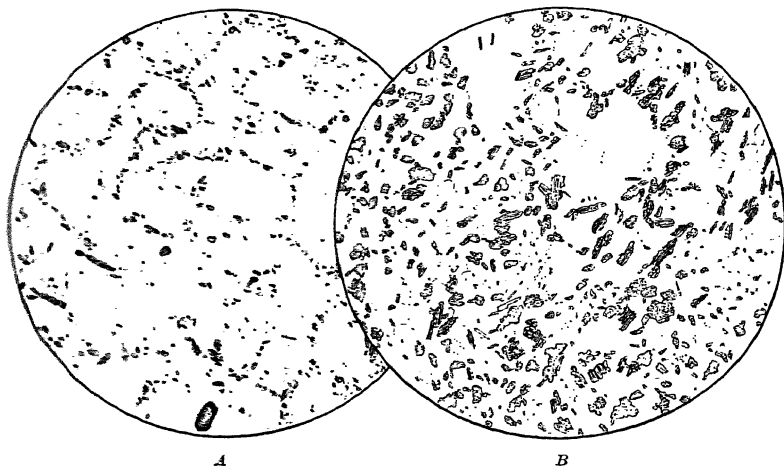


FIG. 23.—METAMORPHOSED ARENACEOUS ROCKS, near the Lausitz Granite, Saxony; $\times 25$.

A. Quartzite with some biotite and epidote, the distribution of these outlining the grains of the original sandstone. At the bottom is a small crystal of zircon, unaffected by the metamorphism.

B. This belongs to a somewhat higher grade of metamorphism. Numerous little flakes of biotite are scattered through the mosaic of quartz (with some feldspar), only indistinctly and in places marking the outlines of the original clastic grains.

that this is more likely to befall a felspathic sandstone than a purely quartzose one. In the isle of Soay, near Skye, the Torridon Sandstone is vitrified at its contact with certain basic and ultrabasic sills of no great thickness.³ It has yielded a clear glass, enclosing very numerous minute crystals of cordierite, magnetite, and sometimes tridymite, with corroded relics of quartz (Fig. 22, A). Inclusions of sandstone

¹ Reynolds, *Quart. Journ. Geol. Soc.*, vol. lxiv (1908), plate lii, fig. 6.

² *Quart. Journ. Geol. Soc.*, vol. lxxviii (1922), pp. 239-40, and plate vii, fig. 5.

³ *Tertiary Igneous Rocks of Skye (Mem. Geol. Sur. U.K., 1904)*, pp. 245-6, and plate xxi, fig. 3.

in basalt are often partly vitrified, and numerous occurrences have been described under the name 'buchite'. The pale or brown glass contains minute crystals of cordierite, mullite, and other minerals. Analyses¹ show from 3 to 5 per cent. of water in the inclusion as a whole, while for the glass the figure may be as high as 10 or 12. Clearly an abundant supply of solvent has been present, which has been fixed in the buchite, while it is lost from the enveloping basalt.

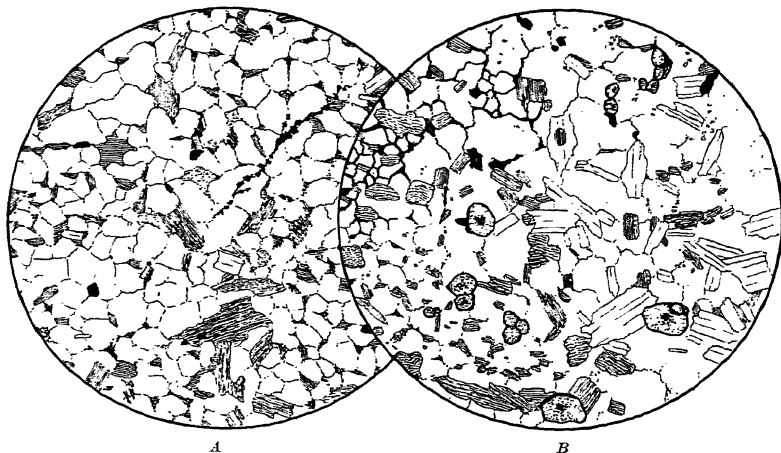


FIG. 24.—METAMORPHOSED GRIT, Skiddaw Grit, near the Skiddaw granite, Sinen Gill, Cumberland; $\times 25$.

A. Biotite-Quartz-Hornfels: a mosaic of quartz and biotite, with some muscovite and magnetite.

B. A more advanced grade of metamorphism, in which garnet also figures. The rock shows banding, the right half of the field being of coarser grain and containing muscovite, while the left half is richer in biotite.

THERMAL METAMORPHISM OF MORE IMPURE ARENACEOUS SEDIMENTS

In a sandstone composed entirely of quartz, or of quartz and fresh felspar, no chemical reaction can be set up in metamorphism; and most of the accessory minerals of detrital origin undergo no change other than recrystallization. This may take place sooner or later, according to the nature of the mineral. Rutile and tourmaline recrystallize at a very early stage; magnetite, muscovite, etc., follow in their turn; only zircon remains untouched in the highest grade of metamorphism (Fig. 22, B). It is otherwise with such substances as chlorite, sericite, kaolin, limonite, calcite, etc. These are decomposi-

¹ Lemberg, *Zeits. Deuts. Geol. Ges.*, vol. xxxv (1883), pp. 563-8.

tion-products, which whether formed before or after the deposition of the sediment, are essentially low-temperature minerals. They are very ready to enter into various reactions with one another and with quartz, and some of these reactions demand no great elevation of temperature. Sericite, chlorite, and limonite may give rise to biotite; calcite and kaolin to epidote; chlorite, calcite, and quartz to augite (Fig. 20, *B*); and so for other combinations. These various new minerals, at their first appearance, figure as numerous little flakes or granules in the interstices of the quartz-grains, and serve to indicate

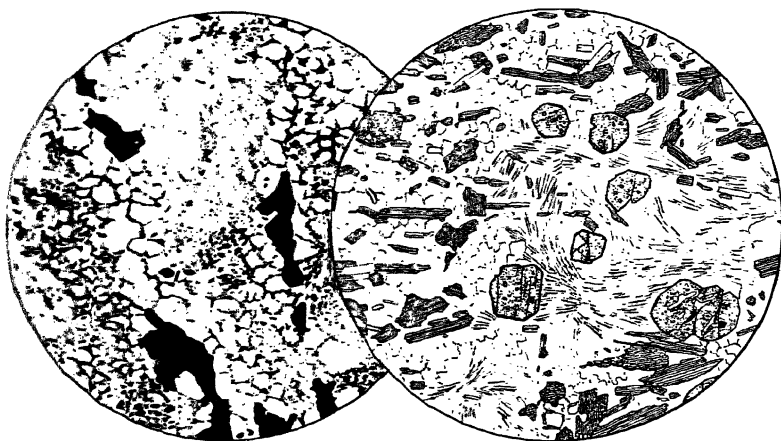


FIG. 25.—HIGHLY METAMORPHOSED GRITS, in the Silurian, near the granite of New Galloway; $\times 25$.

A. This rock has had a cement of iron-oxide, now represented by a network of magnetic granules and minute octahedra. There is also some pyrrhotite.

B. The clear part is a mosaic of quartz with some felspar and cordierite. Through this are scattered biotite, muscovite, garnet, and swarms of minute sillimanite-needles.

the original clastic nature of the rock, even after the quartz itself is recrystallized to a new mosaic. With advancing metamorphism this fades out in consequence of the enlarged latitude of (Fig. 23).

An analogous case is presented by radiolarian cherts in the South of Scotland, where they come within the aureoles of the Galloway granites.¹ At first minute flakes of biotite appear scattered through the rock, except in clear oval spaces which represent radiolarian tests. Later the outlines of these are obliterated, while the quartz-mosaic

¹ Horne. *Rep. Brit. Assoc. for 1892 (1893)*, p. 712; *Ann. Rep. Geol. Sur for 1896 (1897)*, pp. 46-7

acquires a coarser texture, and the biotite-flakes become fewer and larger.

Somewhat similar is the behaviour in metamorphism of sandstones with a ferruginous cement. Whether limonite or haematite, this is speedily transformed to magnetite with interstitial occurrence. In this case, however, this original distribution may persist into a high grade of metamorphism (Fig. 25, *A*). The magnetite is either in granules or in strings of little octahedra.

The non-detrital material in sandstones, when it is not ferruginous

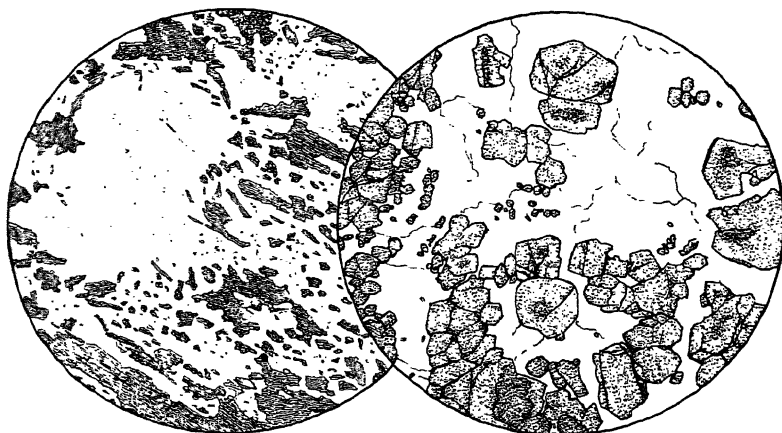


FIG. 26.—HIGHLY METAMORPHOSED GRITS, in the Silurian, near the granite of New Galloway; $\times 25$.

A. Originally an impure pebbly sandstone : now composed of biotite and quartz with some cordierite. The outlines of small pebbles are still indicated, though no longer sharp.
B. From a lenticular streak consisting entirely of red garnet and quartz.

or calcareous, is broadly comparable with the substance of ordinary argillaceous sediments. The new minerals produced in metamorphism are therefore in general the same that we have already met with. But while a slate and an argillaceous sandstone may be represented, at a given stage of metamorphism, by like mineral-associations, the relative proportions of the several minerals will be by no means the same. Rocks resulting from the metamorphism of impure sandstones come therefore to have characters sufficiently distinctive. Quartz is here much more abundant, while the more aluminous silicates, andalusite and cordierite, figure much less prominently. Orthoclase and plagioclase (usually oligoclase) are much more widely distributed than in metamorphosed slates, and are often plentiful: they come

then from the recrystallization of detrital feldspar. Corundum and the spinel minerals which do not form in presence of free silica—are in general absent.

Quartz and feldspar, with cordierite if present, are the minerals with the lowest force of crystallization, and build a mosaic which constitutes the main bulk of the rock. In this as matrix the other minerals are embedded, with idioblastic habit. Since these other minerals have also higher refractive indices, and some of them are they are unduly conspicuous, and the rock, though still

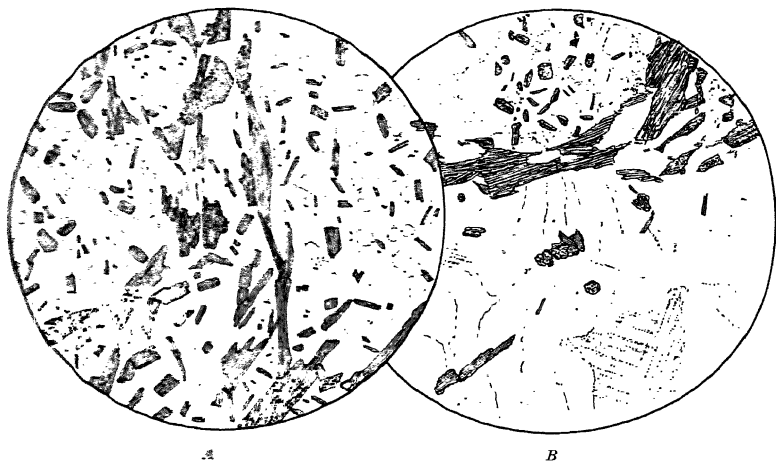


FIG. 27.—CORDIERITE-GNEISS, a highly metamorphosed Devonian greywacke near the Lausitz granite, Saxony; $\times 25$.

The cordierite makes large ovoid and lenticular grains, with numerous inclusions. The rest is a coarse aggregate of biotite, quartz, and (in the second figure) feldspar. See Beck, *Zeit. Min. Pet. Mitt.*, vol. xiv (1893), pp. 332-7.

with a large preponderance of quartz, ceases to have any superficial likeness to a simple quartzite.

In the progressive metamorphism of an argillaceous sandstone there is in general the same sequence of mineralogical transformations that we have traced in the purely argillaceous sediments. An early landmark is the appearance of biotite. The little flakes, at first interstitial between the quartz-grains, take on idioblastic shape as the quartz recrystallizes freely (Fig. 23, compare *A* and *B*), and biotite continues to be prominent, usually in larger flakes, in the higher grades of metamorphism. Garnet marks a more advanced stage, but this mineral, as we have seen, demands special conditions for its formation (p. 54). Good examples of garnetiferous rocks may be

studied on Knocknairling Hill, near New Galloway, in the aureole of the Cairnmore of Fleet granite (Figs. 24, *B*; 25, *B*). The crystals, in addition to the common dodecahedron, show sometimes the trapezohedral form, which is known to be characteristic of the manganese-bearing garnets.

Of the more aluminous silicates, cordierite is the most common, but in the highest grade of metamorphism sillimanite becomes a characteristic constituent, occurring as usual in very numerous fine needles (Fig. 25, *B*). The rocks then may acquire a notably coarse texture; so that the principal minerals, often including feldspars, can be readily identified on a specimen. Owing to the enlarged latitude of diffusion, even quartz-pebbles may be reduced to rather vague patches with ill-defined outline (Fig. 26, *A*). There is for the same reason, in this highest grade of metamorphism, a strong tendency to the segregation of particular minerals in lenticles and inconstant bands. On Knocknairling Hill there are streaks, an inch or two in width, composed wholly of garnet and quartz (Fig. 26, *B*). Even cordierite, when abundant, may form ovoid and lenticular patches of some size, crowded, as is usual in this mineral, with inclusions of biotite and quartz (Fig. 27). In this way, owing to slight original differences between successive seams, exaggerated by a process of segregation, there arises a pronounced gneissic banding. The rocks may be styled *sillimanite-* or *garnet-* or *cordierite-gneisses*, according to the most distinctive mineral which they present.

CHAPTER VI

THERMAL METAMORPHISM OF CALCAREOUS SEDIMENTS

Pure Carbonate-rocks—Special Features of Semi-calcareous Rocks—Thermal Metamorphism of Impure Non-Magnesian Limestones—Thermal Metamorphism of Impure Magnesian Limestones.

PURE CARBONATE-ROCKS

UNDER the head of calcareous rocks are comprised in the first place those which consist wholly or mainly of carbonates, viz. the carbonates of calcium and magnesium and in less abundance those of iron and manganese. The non-calcareous element in such rocks may be of argillaceous or arenaceous nature, or may be material of direct volcanic origin. The behaviour of calcareous and semi-calcareous rocks in thermal metamorphism presents some features which differentiate these deposits fundamentally from non-calcareous sediments, and the new minerals produced are also in great part different. Moreover, a very moderate content of carbonate in a sediment is enough to determine its metamorphism along these special lines. For this reason we shall group together here, not only limestones and dolomites, pure and impure, but also rocks which the field-geologist would name calcareous shales, sandstones, or tuffs.

We will consider first a pure carbonate-rock. An ordinary limestone, as laid down, is essentially of calcic carbonate with only a small proportion of magnesian. It may, without any change in total composition, suffer a recrystallization by aqueous agency at ordinary temperature; aragonite, if present, being transformed to calcite in the process. Again, it may undergo a more radical change, metasomatism, one half of the lime being replaced by
to give dolomite; a process sometimes almost contemporaneous with deposition, sometimes long subsequent. Another metasomatic change, often associated with dolomitization, is the replacement of calcic by ferrous carbonate, yielding chalybite. All these changes, not implying metamorphism in our acceptation of the term, involve nevertheless a total alteration in the fabric of the rock, with obliteration of organic and other original structures except those of the larger order.

Since a limestone may be partially or wholly dolomitized, the molecular ratio MgO : CaO for the rock in bulk may have any value up to unity, but not higher. Magnesite is not found in this association, but belongs to altered igneous rocks of the ultrabasic group.

The metamorphism of a pure carbonate-rock is necessarily a simple process and without gradations. The dissociation of a carbonate, since it involves liberation of a gas, is a reaction resisted by pressure. Under the normal conditions of thermal metamorphism the pressure is always sufficient to prevent the dissociation of calcite in a pure carbonate-rock, and a simple non-magnesian limestone merely recrystallizes, yielding an even-grained *marble*. Such a marble differs in no wise from one recrystallized at ordinary temperatures. As seen in section, the grains are of irregular shape, meeting one another in sinuous or zigzag boundaries.

The behaviour of dolomite in thermal metamorphism is not always the same. In some cases it merely recrystallizes, like calcite. A *dolomite-marble*, however, is usually of finer grain than one of calcite, and the structure is of a simpler type. Sometimes indeed the individual grains offer some suggestion of crystal-shape, always that of the primitive rhombohedron. Under different conditions, viz. with a lower pressure, dolomite dissociates, but only as regards its magnesian part,¹ so that the reaction implies dedolomitization :



The resulting rock is accordingly a *periclase-marble*, composed of periclase and calcite. The periclase, a mineral of pronounced idiomorphic habit, appears as little octahedra embedded in the calcite matrix. It has, however, almost always suffered change by hydration, and is then represented by flaky pseudomorphs of brucite, Mg(OH)₂ (Fig. 28, A). The rocks known in the Tyrol and elsewhere by the names *penecatite* and *predazzite* are of this nature, and good examples are found in Skye and in the Assynt district of Sutherland. *Penecatite*, formed from a pure dolomite-rock, has calcite and brucite in equal molecular proportions. It is a close-grained white rock with the very low specific gravity 2.57. *Predazzite*, derived from a partly dolomitized limestone, has a larger proportion of calcite.

Ferrous carbonate, like that of magnesium and probably more easily, suffers dissociation when heated under natural conditions, the resulting product being magnetite. In Sweden and elsewhere there are bedded magnetite-ores which have been attributed to the meta-

¹ The dissociation-temperature at a pressure of one atmosphere is for calcic carbonate 898° C., but for magnesian carbonate only 402°.

CALCAREOUS SEDIMENTS

of chalybite, but these are intercalated among crystalline

A like transformation may sometimes be observed on a small scale even against a basalt dyke.¹ When sulphides are involved as well as carbonates, the reactions are more complex. Schneiderhöhn² has described the thermal metamorphism of some Westphalian ore-deposits, in which the characteristic reaction is the replacement of chalybite and chalcopryrite by haematite and bornite, the latter mineral reverting on cooling to chalcopryrite and chalcocite.

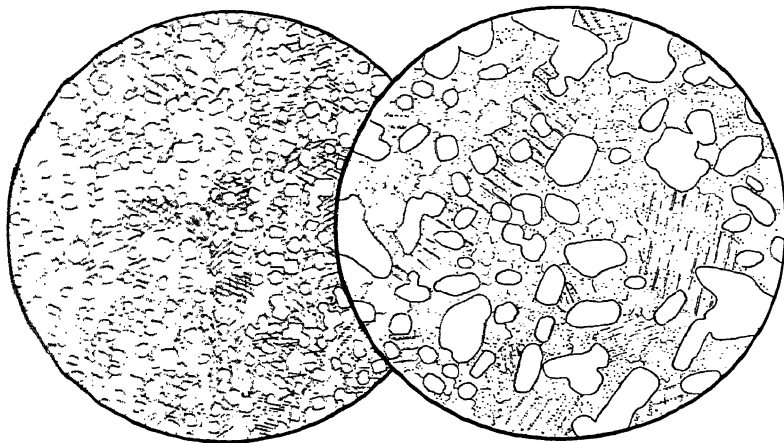


FIG. 28.—METAMORPHOSED DOLOMITIC ROCKS; \times

- A. Peneatite (brucite and calcite), Kilchrist, Skye.
B. Ophicalcite (serpentine and calcite), Ledbeg, Sutherland.

and zinc carbonates too are easily decarbonated by heat. At Franklin Furnace, in New Jersey, thermal metamorphism of dialogite has given rise to hausmannite and franklinite. Of these the former, a tetragonal mineral, is perhaps Mn_2MnO_4 , while the latter is of the magnetite type, and has the approximate composition $MnFe_2O_4$, with some replacement of manganese by zinc.

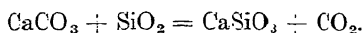
SPECIAL FEATURES OF SEMICALCAREOUS ROCKS

We turn now to rocks which, in addition to carbonates, contain a certain amount of non-calcareous material, which may be regarded as an impurity. If we set aside a possible admixture of volcanic ash, the extraneous material is in general siliceous or argillaceous, and the substances of most importance in the chemistry of the meta-

¹ Busz, *Centr. f. Min.*, 1901, pp. 489-94.

² *Zeits. Krist.*, vol. lviii (1923), pp. 309-29.

morphism are silica and alumina. We have to do with a large number of possible reactions between the calcareous and the non-calcareous constituents of the rock, the simplest type being :



Calcite, which by itself would recrystallize without change, is, under any but the greatest pressures in thermal metamorphism, readily decomposed when silica is present to take the place of the expelled carbon dioxide. Dolomite is *à fortiori* even more readily affected. The actual reactions are generally more complex than that set forth as a type, and the resulting products in different cases include a long list of minerals—silicates and aluminosilicates of magnesium and calcium.

Rocks which are partly carbonate, partly non-carbonate, whether they be impure limestones and dolomites or calcareous shales and slates, have, as already remarked, certain characteristics which differentiate their metamorphism from that of other classes of rocks. In their initial state they present an example of '*false equilibrium*'. The calcareous and non-calcareous elements are in an enforced association which has no relation to true chemical equilibrium; and if no reaction takes place between them, it is merely because at atmospheric temperature the rate of any possible reaction is infinitely small. The rate being accelerated by rise of temperature, reactions come into play, and proceed with a rapidity limited only (since they are endothermic) by the supply of heat. In most other rocks the process is retarded by the very small quantity of solvent present, but here this is reinforced by a copious supply of carbon dioxide liberated by the reactions themselves. The peculiar characters thus inherent in the metamorphism of rocks of this class have important consequences, some of which may be noted in this place.

One result of the promptitude and rapidity of the reactions between calcareous and non-calcareous material is, that we cannot recognize here any such gradations as we can distinguish in the early stages of advancing metamorphism in simple argillaceous sediments. The reactions in question, not only begin, but are completed, at an early stage of metamorphism, as estimated by distance from an igneous contact or by comparison with neighbouring non-calcareous sediments. Where an ordinary shale shows only the beginning of change, a limestone had its impurities already converted to new minerals, and a calcareous shale is totally reconstituted, with loss of all its carbon dioxide. The most striking instances of '*selective metamorphism*' have arisen in this way.

Another consequence of the rapid formation of new minerals is the frequent failure to establish chemical equilibrium. In this way may be produced in particular instances various metastable forms, or again anomalous associations of minerals. The number of distinct minerals in some of these assemblages is in excess of that prescribed by Goldschmidt's adaptation of the Phase Rule (p. 4). Such aberrations are probably very general in the first rapid metamorphism, but, unless cooling also is rapid, they are likely to be obliterated by adjustment of equilibrium.

Another respect in which partly calcareous rocks are peculiar is that the new minerals formed depend from the first upon the total composition of the rock. More precisely, they depend upon the composition of the carbonate part, whether purely calcic or partly magnesian, and of the non-carbonate part, whether merely siliceous or also aluminous. The reason for stating the matter in this way will appear, if we examine the list of minerals actually found in this association. They are very numerous, and a given metamorphosed rock may embrace a considerable number of distinct mineral-species. We will enumerate in the first place only those which are of most common occurrence. The purely calcic minerals, beginning with that richest in lime, are wollastonite, lime-garnets, idocrase, prehnite (of doubtful status), sphene, zoisite and epidote, and anorthite (with other lime-bearing feldspars). Of these wollastonite is the only simple silicate: the rest, except the silico-titanate sphene, are aluminosilicates, all of orthosilicate type. All, with the exception of sphene and anorthite, are foreign to igneous rocks. The magnesian and partly magnesian minerals, on the other hand, include both ortho- and meta-

s, normally non-aluminous, and are comparable with common minerals—olivines, pyroxenes, and amphiboles. Of the olivines, forsterite, with little or no iron, is the usual variety. The pyroxenes are of the monoclinic division, and are represented generally by diopside. Of the amphiboles, tremolite and allied actinolitic varieties are the most common, but various coloured hornblendes are also found. Fuller knowledge of their composition is a desideratum, more especially as regards their possible content of alumina.

OF IMPURE NON-MAGNESIAN LIMESTONES

The simplest case is that of a non-magnesian limestone in which the only impurity is silica, either as quartz or as chert of organic origin. No great elevation of temperature is necessary to initiate a reaction, and the product is the metasilicate *wollastonite*. It is noteworthy that the orthosilicate, which forms readily from a melt of

appropriate composition, is unstable under the conditions of metamorphism, and is of extremely rare occurrence. The stability-relations between the monoclinic and triclinic forms of wollastonite have not been determined. Peacock¹ suggests that the former, which he names parawollastonite, belongs to the lower temperatures. The highest form pseudowollastonite is not to be expected in metamorphism of the ordinary kind, being stable only above 1150° C.² Wollastonite appears as lustrous white crystals, often of considerable size. With a sufficiency of silica, the limestone may be completely decarbonated, yielding a simple wollastonite-rock (Fig. 2, B, above). Since the ideal composition which we have supposed is not often realized in fact, wollastonite is commonly accompanied by at least small amounts of other silicates. Thus the presence of a little magnesia is enough to produce some diopside (equivalent to wollastonite *plus* enstatite), while any aluminous material present is likely to give rise to grossularite (with the composition 3 wollastonite *plus* alumina).

Consider now a non-magnesian, or practically non-magnesian, limestone containing a noteworthy quantity of argillaceous impurities. Here is the material for a number of possible aluminosilicates. The more important are all of the orthosilicate type, and have alumina and lime in molecular proportions as follows :

Idocrase, ³ $\text{Ca}_{19}\text{MgAl}_{12}(\text{SiO}_4)_{18}(\text{OH})_4$	6 : 19,
Grossularite, $\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$	1 : 3,
Zoisite, $\text{Ca}_2(\text{AlOH})\text{Al}_2(\text{SiO}_4)_3$	3 : 4,
Anorthite, $\text{CaAl}_2(\text{SiO}_4)_2$	1 : 1.

They fall accordingly into two pairs, the one, relatively poor in alumina, being characteristic of metamorphosed limestones, the other, rich in alumina, of calcareous shales.

The most common product of metamorphism in argillaceous limestones is a lime-garnet, which forms very readily. It is sometimes produced in abundance even in the vicinity of a large dyke (Fig. 29). Large crystals may thus be rapidly built up, crowded with foreign matter, their growth being analogous to that of early crystals of andalusite and cordierite in argillaceous rocks (p. 49). Since most limestones are poor in iron, the garnet is usually a *grossularite*.

¹ *Amer. Journ. Sci.* (5), vol. xxx (1935), p. 525.

² It has been recorded by McLintock in marls metamorphosed by the combustion of hydrocarbons; *Min. Mag.*, vol. xxiii (1932), pp. 207-26.

³ This formula, equivalent to 6 grossularite + $\text{CaMg}(\text{OH})_4$, was deduced by Machatschki from a large number of analyses: *Cent. Min.*, 1930, A, p. 293. Warren and Modell, from an investigation of the crystal-structure, give $\text{Ca}_{10}\text{Mg}_2\text{Al}_4\text{Si}_9\text{O}_{34}(\text{OH})_4$: *Zeits. Krist.*, vol. lxxviii (1931), pp. 422-32.

Varieties rich in iron, often found in plutonic contact-belts in company with ferriferous pyroxenes, have a special manner of origin, to be discussed later. Its high force of crystallization causes garnet to be idioblastic against most other minerals, wollastonite usually excepted. The forms are the dodecahedral and less commonly the trapezohedral. The well-known peculiarities of these lime-garnets are perhaps connected with their rapid development. They show distinct zones of growth: they are more or less decidedly birefringent, this property varying in successive zones: and they exhibit polysynthetic twinning.

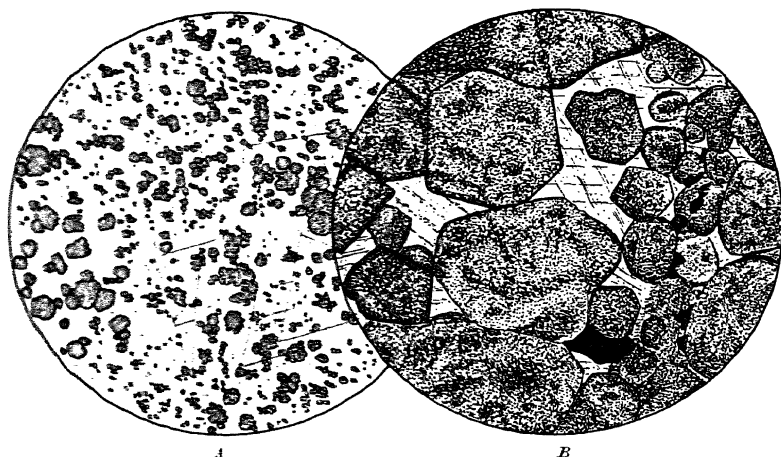


FIG. 29.—LIME-GARNET (GROSSULARITE) EMBEDDED IN RECRYSTALLIZED CALCITE, from calcareous rocks metamorphosed near dolerite dykes; $\times 25$.

A. Jurassic Limestone, Carnasunary, Skye: showing a crowd of small crystals.
 B. Carboniferous Limestone, Plas Newydd, Menai Straits. The garnet is birefringent and with poly-synthetic twinning. Rapidly formed, the crystals enclose a large amount of foreign matter. The opaque mineral is pyrrhotite.

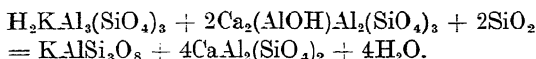
made evident in virtue of the birefringence. Grossularite is very often found in company with wollastonite.

Another common associate of lime-garnet is *idocrase* (vesuvianite), which has a very similar composition. Since, however, hydroxyl makes an essential part of its constitution, pressure must be one ruling condition of its formation. As a normal product of thermal metamorphism, idocrase is xenoblastic against wollastonite and grossularite but idioblastic against quartz; usually also against calcite, though here the relations are rather variable. It should be added that idocrase is often found also partially or totally replacing grossularite as a result of later change (retrograde metamorphism).

The place of *zoisite* is often taken by *clinozoisite* or a slightly

ferriferous epidote. These allied minerals form readily in a calcareous sediment which is also sufficiently aluminous, and, like grossularite, may be produced in abundance in proportion as the bulk-composition of the rock when decarbonated approximates to that of the mineral in question. Zoisite and epidote are strong minerals, but weaker than wollastonite and grossularite.

Another lime-silicate of like associations is *anorthite*. Its composition is equivalent to that of wollastonite *plus* andalusite, and to produce it the non-carbonate part of the rock must be rich enough in alumina to yield andalusite. Anorthite, however, belongs to a higher temperature-grade than the zoisite-epidote-minerals, and these may be regarded as a stage in the formation of the lime-felspar in advancing metamorphism. The felspar is not always anorthite. A mixed sediment may carry more or less detrital albite, or again albite may be generated at the expense of white mica by reactions already discussed (p. 56); and between this and the anorthite there arise accordingly various felspars of intermediate composition. Often, too, a certain amount of *orthoclase* or *microcline* figures in the more highly metamorphosed sediments of this class. The production of potash-felspar from muscovite and of lime-felspar from the zoisite-epidote minerals may be parts of the same reaction:



The felspars are low in the crystalloblastic series, and the potash-felspars in particular constantly show a xenoblastic habit.

The zony arrangement of different varieties of plagioclase in the same crystal, which is a conspicuous feature in so many igneous rocks, is much less in evidence in metamorphic felspars; but it is found, and presents some points of interest. In igneous rocks, allowing for some anomalies connected with supersaturation, the rule is that the core of the crystal is more calcic and the margin more sodic. In the crystalline schists, as remarked by Becke, the reverse is found, though not without exceptions. According to Goldschmidt,¹ the zoned felspars of thermally metamorphosed rocks present an intermediate case. In all the more calcic felspars the crystal is most calcic in its core, and grows progressively more sodic, tending to a composition Ab_3An_1 at the margin. Varieties with an average content of An of 26 to 20 per cent. show little or no zoning, and the more sodic felspars are most albitic at the centre.

The mineral *prehnite* is of not infrequent occurrence in meta-

¹ *Vidensk. Skr.* (1911), No. 11, pp. 292-301.

morphosed calcareous rocks, and is regarded by some petrologists as a normal product of thermal metamorphism; but its status as such is not beyond question. In many occurrences it has certainly been produced by later reactions at the expense of other lime-silicates, and this is often manifest from its mode of occurrence.

A common product of metamorphism in argillaceous limestones is *sphene*. Its composition is equivalent to that of wollastonite *plus* rutile, and it owes its origin to the minute rutile needles which are so widely distributed in argillaceous sediments. A direct reaction between rutile and calcite would yield perovskite; but this mineral is not known as a simply thermo-metamorphic product away from igneous contacts.

THERMAL METAMORPHISM OF IMPURE MAGNESIAN LIMESTONES

The metamorphism of dolomites and partly dolomitic limestones carrying various impurities presents some features of special interest. The salient fact that emerges is that *silica reacts with the magnesian in preference to the calcic carbonate*. It follows that, unless disposable silica is present in amount sufficient for complete decarbonation of the rock, one incident of the metamorphism is *dedolomitization*.¹ This is an effect which we have already observed in some pure carbonate-rocks as a consequence of the fact that the magnesian carbonate by itself is more easily dissociated than the calcic (p. 77).

Consider first a dolomitic rock containing silica as its only impurity. Here are the materials for making a number of compounds: the simple lime metasilicate wollastonite and orthosilicate larnite; the double silicates diopside, tremolite, and monticellite; and the purely silicates enstatite, anthophyllite, and forsterite. We find in fact that the first mineral to form, and with a limited supply of silica the only mineral, is the magnesian *forsterite*. This moreover, unlike wollastonite, is an orthosilicate, taking up therefore a double quantity of magnesia. The two other orthosilicates, monticellite and larnite, are unstable forms, and the magnesian metasilicates, enstatite and anthophyllite, are not found in this connexion. The commonest resulting rock is thus a forsterite-marble (Fig. 30, *A*). Idioblastic crystals of forsterite are set in a matrix which is of calcite or of calcite and dolomite, according as more or less silica was originally present. The forsterite has often been replaced by a pale serpentine, giving the rock known as *ophicalcite* (Fig. 28, *B*). There are sometimes interesting special structures, which are well exhibited in the metamorphosed cherty dolomites of Skye. Here much of the contained silica was

originally in the form of sponges, and from these, at a time anterior to the metamorphism, had become diffused into the surrounding rock. Its distribution was of that rhythmical kind studied by Liesegang,¹ resulting in numerous thin concentric shells alternately rich and poor in silica, and these are now represented by alternations of serpentine and calcite. The details of the structure at the same time illustrate those pseudo-organic appearances which once passed under the name of 'Eozoon'.²

If the original dolomitic rock contained more silica than would

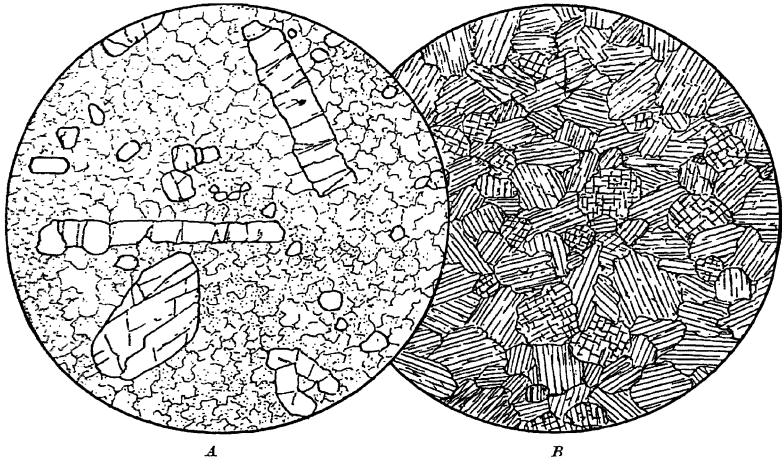


FIG. 30.—METAMORPHOSED CHERTY DOLOMITES in the Cambrian of Skye; $\times 25$.

A. Forsterite-Marble, near the granite of Kilchrist: idioblastic crystals of forsterite set in a matrix of calcite.

B. Diopside-rock, near the gabbro of Broadford. This represents a richly cherty band, now completely converted to diopside. Note the decussate structure.

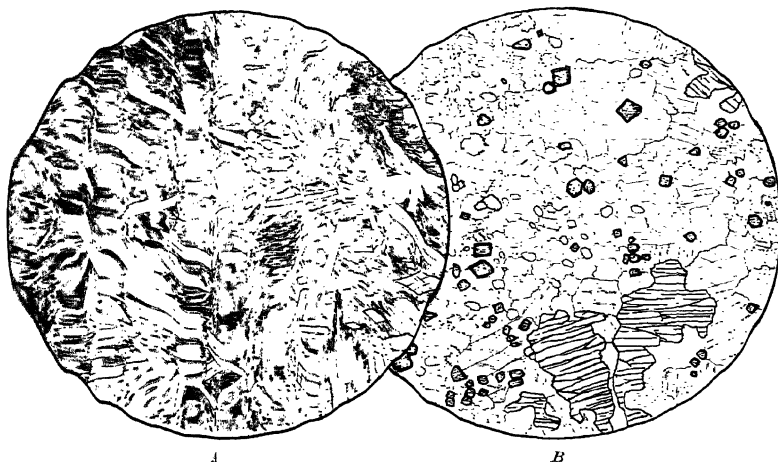
suffice to convert all the magnesia to forsterite, a lime-bearing silicate makes its appearance. This, however, is not wollastonite but the double silicate *diopside*, which is then found accompanying or replacing the forsterite. In Skye it takes the place of that mineral in certain beds or sometimes in patches which represent the vanished sponges, and there are even cherty seams converted to solid diopside-rock (Fig. 30, B). It should be observed that the formation of diopside does not in itself import dedolomitization; but, if the mineral is subsequently converted to serpentine and calcite, the same result is

Diffusionen (1913).

¹ King and Rowney, *Proc. Roy. Ir. Acad.* (2), vol. i (1871), pp. 132-9; *An Old Chapter of the Geological Record* (1881).

reached indirectly. Adams and Barlow¹ have explained in this way the origin of some serpentine marbles in Ontario, but doubtless the more usual derivation of serpentine in such rocks is from forsterite.

A colourless *tremolite*, in prismatic crystals or thickly felted needles, is a mineral of less general distribution in this connexion (Fig. 31. A). In Skye it is found especially as a skin investing the forms which represent siliceous sponges. Its situation here, with diopside inside and forsterite outside, accords with the intermediate composition of the amphibole. Tremolite does not, however, enter the inner ring



31.—METAMORPHOSED CHERTY DOLOMITES, near Kilchrist, Skye; $\times 25$.
 A. Tremolite-Marble: a dense aggregate of little prisms and fine needles of tremolite.
 B. Diopside-Marble with small octahedra of spinel.

of the aureoles, and it is presumably unstable at the highest temperatures of metamorphism. It is to be noted that the now generally accepted formula of this mineral is $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$, involving constitutional hydroxyl.

The ferrous and manganese carbonates, like the magnesian and in preference to the calcic, enter readily into reaction with silica. In a merely ferruginous limestone or dolomite the iron goes into such as *actinolite* and *hedenbergite*. The metamorphism of an *chalybite*-rock may give rise to *ilvaite*, with the formula $\text{Ca}_2\text{Mg}_4\text{Si}_8\text{O}_{22}(\text{OH})_2$. From impure carbonate-rocks rich in manganese there may be formed a variety of *rhodonite* with its zinc-bearing variety *fowlerite*.

Haliburton and Bancroft Areas (Mem. Geol. Sur. Can., 1910),

Consider next the metamorphism of a magnesian limestone containing aluminous as well as siliceous impurities. If only a small quantity of alumina be present in a disposable form, it may be taken up into an amphibole, some member of the edenite-pargasite series being formed instead of tremolite.¹ In a higher grade, where the amphiboles cease to be stable, the alumina does not go into the pyroxene, but makes *spinel*, which is a very characteristic accessory mineral in forsterite- and diopside-marbles. It appears in little octahedra, colourless or of violet tint (Fig. 31, *B*).

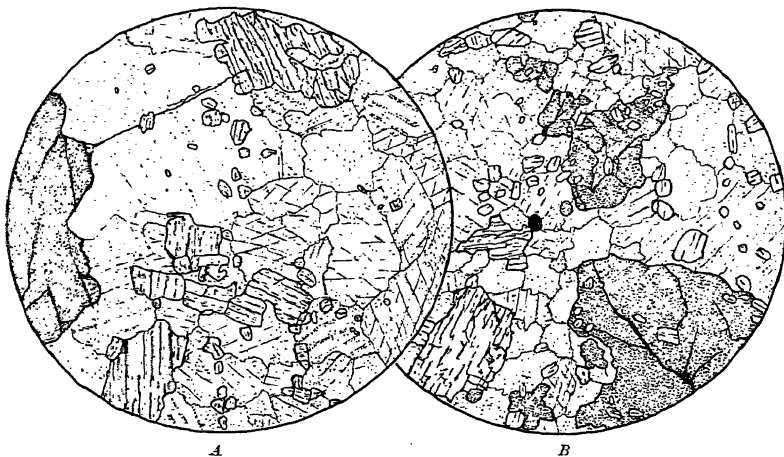


FIG. 32.—CRYSTALLINE LIMESTONES WITH GROSSULARITE AND DIOPSIDE, Aberdeenshire; $\times 23$.

The examples selected are of coarser grain than most rocks of this type. In *B* the irregularly shaped garnet, enclosing grains of diopside, suggests a hasty crystallization.

With a larger content of alumina the conditions are quite changed. Since no magnesian aluminosilicate figures in our list, the alumina goes now to make grossularite or idocrase. Diopside is found in company with one or both of these minerals, but forsterite is no longer formed (Fig. 32). In rocks not too rich in alumina, or too highly magnesian, wollastonite figures in addition. The association grossularite-diopside-wollastonite or idocrase-diopside-wollastonite is characteristic of a widespread class of metamorphosed calcareous rocks, the relative proportions of the minerals depending on the ratios $\text{Al}_2\text{O}_3 : \text{MgO} : \text{CaO}$ in the bulk-analysis of the rock. If the disposable alumina present passes a certain limit, the simple silicate wollastonite is ruled out, and the anorthite molecule takes its place.

¹ Tilley, *Geol. Mag.*, vol. lvii (1920), p. 454.

This, however, is a simplified view of the actual case. In an ordinary argillaceous limestone other components are present besides alumina and silica, the most important being alkalies, iron-oxides, titania, and perhaps sulphur. Some magnesia also enters in the form of detrital chlorite. The possibilities in respect of new minerals are thereby considerably enlarged. Note in the first place that some of the non-carbonate minerals in such a mixed sediment may merely recrystallize without change. This is true, for example, of *graphite* of detrital *tourmaline*, and in the lower grades of metamorphism of *muscovite*. A special case, which need not be discussed in detail, is that of a calcareous tuff, in which such minerals as feldspars and pyroxenes may suffer no change beyond recrystallization. The finely divided *albite*, which is present in many argillaceous limestones, at first recrystallizes without other change. In a higher grade it is likely to become associated with new-formed anorthite, and we find accordingly *intermediate feldspars* ranging from oligoclase to bytownite. In a high grade, too, we often see some potash-feldspar, either *orthoclase* or *microcline*, and this can come only from the dissociation of white mica, present as sericite in the original sediment. Any original limonite is, as a first step, reduced to *magnetite*: but at least part of the iron-oxides is ultimately taken up into the silicate-compounds, viz. as the hedenbergite molecule in diopside and perhaps as andradite in grossularite. Titanic acid, originally present as rutile, goes to make *sphene*: the titaniferous garnets, melanite and schorlomite, found in alkaline igneous rocks and in some contact-belts, have no place among normal products of metamorphism. There is usually sufficient silica present to convert all the alumina to silicates, but, if silica is deficient, a mineral of the spinel group is formed, often a *pleonaste*. Among the various types of metamorphosed limestones in the Carlingford district Osborne¹ has noted one composed essentially of diopside, grossularite, spinel, and calcite; and in the same district calcareous rocks which have undergone pneumatolysis as well as metamorphism contain pleonaste as an abundant constituent (Fig. 53, B). Finally it may be remarked that many calcareous rocks have a certain content of sulphides. In a high grade of metamorphism pyrites is converted to *pyrrhotite* by the loss of part of its sulphur. The change takes place at some temperature above 500°, depending of course upon the pressure.² Near an igneous contact, however, pyrrhotite has often a pneumatolytic

¹Mag., vol. lxxix (1932), p.

and Johnston, Amer. J. Sci. (4), vol. xxxiii (1912).

CHAPTER VII

THERMAL METAMORPHISM OF CALCAREOUS SEDIMENTS (continued)

Lime-silicate-rocks—Stable and Metastable Associations—Goldschmidt's Classification of Types of Hornfels.

LIME-SILICATE-ROCKS

THE general course of metamorphism in impure limestones and dolomites is simple. By such reactions as we have specified, with rising temperature, the carbonates (and first the magnesian carbonate) are replaced by new minerals, of which the most characteristic are magnesia- and lime-bearing silicates, carbon dioxide being concurrently expelled. The reduced amount of residual (recrystallized) calcite finally associated with the new minerals gives a rough measure of the degree of impurity of the original sediment. If the non-calcareous part was initially in such quantity and of such a nature as to react with the whole of the carbonates, no calcite will remain, and we have what is conveniently styled a *lime-silicate-rock*. Mineralogically the name covers a rather wide range of diversity. In addition to the mineral-associations already noticed, a certain amount of quartz may enter, when the original rock was of a gritty nature—a mineral which would not be stable in company with calcite under the conditions of thermal metamorphism. In respect of grain-size, too, a wide range of difference may be observed. The coarser types are generally those made up mainly of one mineral, or sometimes an intergrowth of two minerals. The more common types, which are of composite nature, tend to illustrate the other extreme. Here the development of crystals of several different minerals from centres in close proximity has often given rise to a very fine-grained aggregate. For such close-grained lime-silicate-rocks, as developed among the metamorphosed Devonian strata round the Cornish granites, Barrow has used the term *calc-flintas*. It is a consequence of the large number of minerals which may possibly enter, that slight differences of initial composition in successive seams may result in very different mineral-associations, and accordingly a finely-banded arrangement is a characteristic feature of the calc-flintas (Fig. 33). In other cases a concretionary structure has

given rise to a concentric arrangement of the new minerals (Fig. 52, *A*, below).

As regards the more important minerals formed in any given case, the controlling factor is to be sought, as we have seen, in the relative proportions of lime, magnesia, and alumina in the original sediment. One particular case is worthy of note. While in a pure carbonate-rock the magnesia (reckoned in molecules) can never be in excess of the lime, this relation is emphatically reversed in any ordinary type of argillaceous sediment. If then a dolomitic limestone

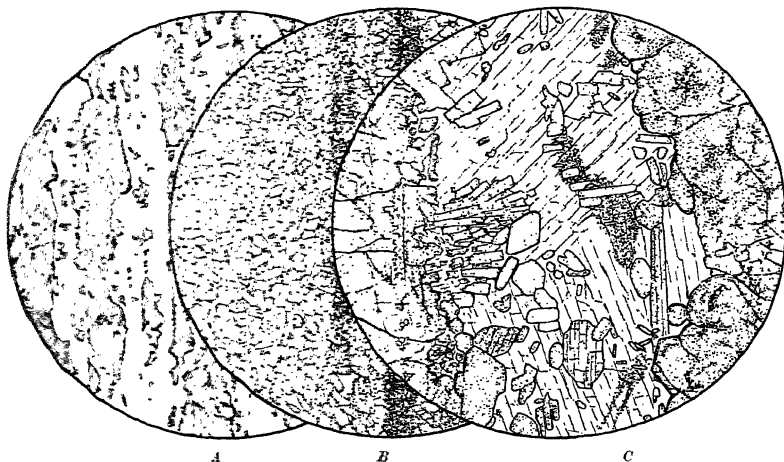


FIG. 33.—LIME-SILICATE-ROCKS (CALC-FLINTAS) from the Devonian of Cornwall and Devonshire; $\times 25$.

A. Glaverghan, near the St. Austell granite. Green hornblende makes discontinuous bands following the original lamination: the rest is a finely granular aggregate of feldspar and quartz.

B. Ivybridge, near the Dartmoor granite: composed of little crystals of diopside with plagioclase.

C. Carnell Hill, near the Bodmin Moor granite. This shows bands of zoisite on the left and garnet on the right: in the middle colourless tremolite enclosing crystals of zoisite.

contains an abundance of foreign material which is largely chloritic in composition, the ratio $\text{CaO} : \text{MgO} (+ \text{FeO})$ in the mixed rock may well be too low to permit the formation of such silicates as garnet, idocrase, and wollastonite. The principal minerals produced are then pyroxenes, amphiboles, plagioclase feldspars, and sphene, giving a well-characterized type of rock. It will be observed that these are all familiar pyrogenetic minerals. Indeed some sediments of the kind in question, apart from their content of carbon dioxide, do not differ much in composition from some basic igneous rocks; and it is natural to find that, in a high grade of metamorphism, this resemblance

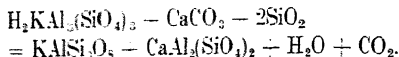
should express itself in a like mineralogical constitution. A good example is a rock in the Ducktown district of Tennessee, originally described as a quartz-diorite.¹ Various types are illustrated on a small scale in the Cornish calc-flintas or in particular bands in that group.

In many partly calcareous sediments the non-carbonate element, instead of being an adventitious admixture, makes up the chief bulk. Such are the deposits styled *calcareous shales, slates, and sandstones*. Here the non-calcareous material is much in excess of what is requisite for the complete decarbonation of all the carbonate present, and the course of metamorphism is in consequence somewhat more complicated. In addition to the class of reactions which we have been discussing, there now come into play others of the kind formerly studied in the metamorphism of simple argillaceous sediments. Nor is it sufficient to picture the two sets of reactions as proceeding independently side by side or successively, for they exercise to some extent a modifying influence upon one another. One way in which this interaction makes itself felt is in ruling out what we may regard as the more extreme products on both sides, i.e. the more highly calcic and the more richly aluminous. The lime-silicates formed in the metamorphism of such a moderately calcareous sediment are characteristically the epidote minerals in a low grade and lime-felspars in a higher. Grossularite and idocrase are found only in bands which were rather more richly calcareous, and wollastonite is absent. Of magnesian minerals there occurs a pyroxene, probably near diopside, or a green hornblende, but not forsterite. On the argillaceous side, biotite often forms freely, and cordierite may be produced in the least calcareous bands, but not andalusite. By considering the composition of the several minerals, it is easy to see what associations are to be expected; and the facts as observed are generally in accord with Goldschmidt's diagram, given on page 99 (Fig. 38). For instance, grossularite and idocrase are not found in company with either biotite or cordierite, while diopside may occur with biotite but not with cordierite (Fig. 34, A).

It should be remarked that the reactions for which we have premised a peculiar promptitude and rapidity are only those which take place between carbonate and non-carbonate. The metamorphism of the argillaceous part of the rock, in so far as it can be regarded separately, is a graduated process, though the adjustment of equilibrium from grade to grade is presumably facilitated by the solvent action of such free carbon dioxide as is present. Again, certain reactions characteristic of an advanced grade of metamorphism will

¹ Keith, *Bull. Geol. Soc. Amer.*, vol. xxiv (1913), p. 684; Laney, *U.S. Geol. Surv. Prof. Pap.* 139 (1926), pp. 19-21.

be promoted in the presence of lime. This is true in particular of the reactions by which alkali-feldspars are produced at the expense of micas (p. 56). Here the anorthite molecule affords a ready way of disposing of the excess of alumina :



The sodic element in the mica gives rise to albite. Orthoclase and plagioclase thus come often to be associated ; but there is no relation between their respective amounts in a rock, for alumina to make

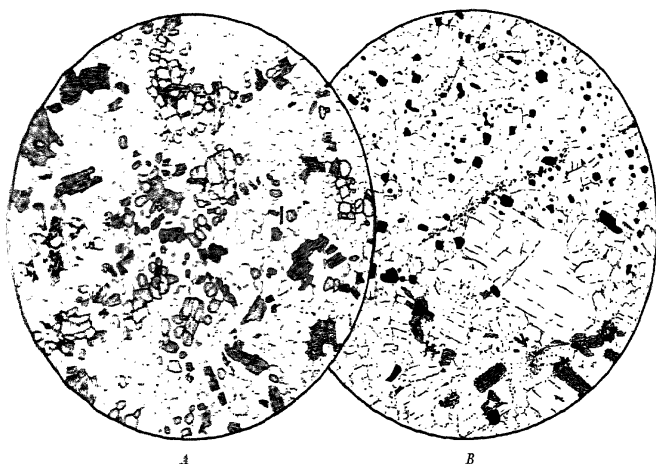


FIG. 34.—METAMORPHOSED CALCAREOUS SLATES, in the aureole of the Carn Chois diorite, near Comrie, Perthshire ; $\times 23$.

A. Diopside-Biotite-Hornfels : composed of diopside, biotite, quartz, orthoclase, and some labradorite.

B. Plagioclase-Cordierite-Hornfels. The most abundant mineral is labradorite, in small crystals, and some of larger size ; with this are cordierite, biotite, magnetite, and a little pyroxene. The sediment was one poor in silica.

may come from other sources, and albite has often been present in the original sediment. In this way arise rocks somewhat rich in plagioclase, usually of some intermediate variety—andesine or labradorite—and containing in addition orthoclase and biotite. The other minerals which may enter depend upon the proportion of lime in the original sediment. The more calcareous shales and slates yield diopside (Fig. 34, A) or in a lower grade sometimes a hornblende ; with a lower lime-content hypersthene may take the place of diopside, or biotite may be the only coloured mineral ; and in only slightly calcareous rocks cordierite comes in (Fig. 34, B).

STABLE AND METASTABLE ASSOCIATIONS

We have already been led to the conviction that under the conditions realized in thermal metamorphism chemical equilibrium is in general quite promptly established. For reasons given, this is especially true when part of the rock metamorphosed is composed of carbonates. With continually rising temperature, various reactions are successively brought into play; and, by observing the results as arrested at different stages, we are able to recognize *successive grades of metamorphism*. To present a schematic view of this succession, defined by particular index-minerals, is a less easy task, in view of the wide range of bulk-composition met with in this class of rocks, which expresses itself in different mineral-associations. Moreover, it is especially in this class that the influence of pressure as an independent controlling factor cannot be disregarded.

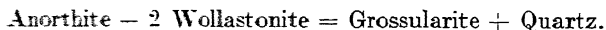
It is only at the lowest temperatures (in purely thermal metamorphism) that carbonates and free silica can coexist without mutual reaction; and the first formation of wollastonite or (in a more argillaceous limestone) of grossularite or idocrase must be placed at a very early stage. Since, moreover, wollastonite and probably grossularite have no upper limit of stability in thermal metamorphism, they can be of no service as index-minerals. Idocrase too may persist to the highest grades, and its dependence on pressure and water-content complicates its stability-conditions. In more richly argillaceous sediments, such as calcareous shales, the first lime-silicates to form are minerals of the zoisite-epidote group, and these give place in a higher grade to lime-felspars. The production of anorthite as a distinct mineral marks always a high grade of metamorphism; but it appears that in presence of albite the zoisite-anorthite reaction is initiated at much lower temperatures and carried on progressively. Any detrital albite contained in the original sediment recrystallizes, as we have seen, at a very early stage in the form of minute granules. When, at a somewhat later stage, the little grains of clear felspar are more developed, it can often be verified that they are no longer pure albite but rather an albite-oligoclase. Comparative study goes to show that oligoclase forms at a higher temperature and andesine and labradorite in turn only in a distinctly high grade of metamorphism. Whether these more calcic felspars can form at all, depends obviously upon the relative proportions of zoisite and albite. If then increased knowledge should establish the different varieties of plagioclase as known index-minerals, they must still be used only with due caution. In calcareous shales as in purely argillaceous rocks, the appearance of a potash-

felspar marks a fairly advanced grade of metamorphism, though it is not to be assumed that the temperature indicated is necessarily the same in both cases (p. 92).

In magnesian limestones and in many of the more impure calcareous sediments some member of the amphibole group may figure among the products of metamorphism: and, since these minerals are found in the lower and medium grades but disappear in a high grade, they are of significance in the present connexion. If such disappearance takes effect (for a given variety of amphibole) at a definite temperature-limit, they will evidently afford valuable indications. This may still be true, within reasonable limits, if these minerals are indeed merely metastable forms, as is perhaps suggested by their often inconstant or sporadic occurrence.

We have hitherto seen little reason to question the thesis laid down at the outset, that in thermal metamorphism chemical equilibrium is in general promptly made good. Some apparent exceptions do not carry conviction, especially those which are cited as showing too many different minerals in association, as judged by the standard of the Phase Rule. Here we must remember the very narrow limits of diffusion and also in some cases the difficulty of determining the exact number of components involved. We do, however, meet with certain mineral-associations which are on the face anomalous, and one of these is worthy of notice.

In the metamorphism of impure calcareous rocks we find grossularite and diopside associated either with wollastonite or with anorthite, but the two last-named minerals seem to be incompatible with one another. The presumption is then that the wollastonite and anorthite molecules combine to make grossularite:



Nevertheless, in the Carlingford district,¹ in Deeside,² and elsewhere, there are occurrences in which wollastonite and a lime-bearing felspar are found in close association, with or without grossularite (Fig. 35). It is no doubt conceivable that the association shown on the right side of the equation is stable below and that on the left above a certain temperature, and that the temperature-range of metamorphism embraces both cases; but in fact the normal and the anomalous may be found near together with nothing to suggest any significant difference of temperature. Important variation of pressure

Geol. Mag., vol. lxi (1932), pp. 223-4.

Trans. Roy. Soc. Edin., vol. lvii (1933), p. 574.

is equally ruled out,¹ and it might seem that the close association of wollastonite and a calcic feldspar is to be explained as an instance of failure to adjust chemical equilibrium. It does not appear, however, that there are actual records of the occurrence of wollastonite with anorthite itself, but only with intermediate varieties of plagioclase; and Osborne has suggested that the explanation may be found in the presence of the albite molecule.

The most indubitable examples of the non-adjustment of equilibrium occur in connexion with special geological conditions. They

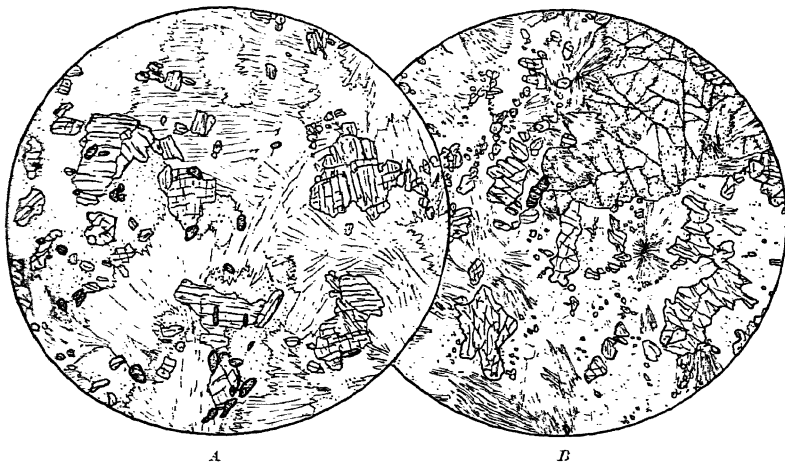


FIG. 35.—ANOMALOUS ASSOCIATION OF WOLLASTONITE WITH CALCIC FELSPARS, Pollagach Burn, near Cambus o' May, Aberdeenshire; $\times 23$.

A. Wollastonite, with fibrous habit and a tendency to radiate arrangement, is seen in contact with bytownite (dull from incipient change). The other minerals are diopside and sphene.

B. Here grossularite occurs in addition. The radiating needles of wollastonite are enclosed both in the clear feldspar (andesine) and in the garnet.

are found, not within a regular aureole, but near contact with some minor intrusive mass; that is, in a place where a high temperature was attained, but cooling was relatively rapid. The conditions, in short, were such as have elsewhere given rise to vitrification in ordinary shales and sandstones (p. 27). In such circumstances the metamorphism of impure calcareous rocks may yield, not only anomalous mineral-associations, but particular *rare mineral-species*, which may be confidently set down as merely metastable forms. Some of these minerals are known only from one or two localities, where perhaps several of them occur together.

¹ Higher pressure would favour the normal (garnet-bearing) association.

CALCAREOUS SEDIMENTS

Among the minerals having this special manner of occurrence must be reckoned the melilites, including gehlenite and other varieties. A well-known locality for melilite¹ is in the metamorphosed Triassic dolomites of Monzoni (Fig. 36, A). More remarkable are the rare orthosilicates of calcium and magnesium:

Monticellite, CaMgSiO_4 ,

Merwinite,² $\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$,

Larnite,³ Ca_2SiO_4 ,

Spurrite,⁴ $2\text{Ca}_2\text{SiO}_4 \cdot \text{CaCO}_3$,

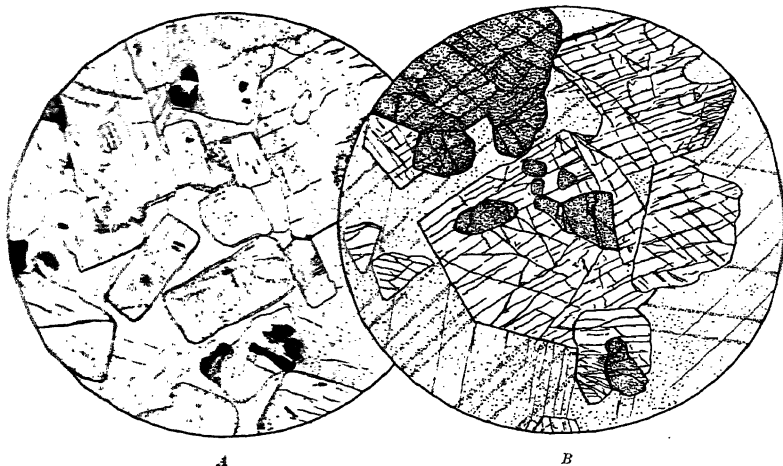


FIG. 36.—RARE MINERALS IN METAMORPHOSED DOLOMITE, Monzoni, Tirol; $\times 23$.

A. Melilite crystals set in calcite.

B. Fassaite and pleonaste in calcite.

the last being a compound of silicate and carbonate. These minerals are found in close association with one another. An interesting occurrence is that described by Tilley from the Chalk metamorphosed by a dolerite intrusion at Scawt Hill, near Larne, Co. Antrim. Here are found spurrite, larnite, melilite, merwinite, and pleonaste (Fig. 37).

Associated with some of these rare species are found also other minerals having an anomalous composition of the kind suggestive of

named gehlenite, but see Buddington, *Amer. J. Sci.* (5), vol. iii pp. 71, 74.

and Foshag, *Amer. Min.*, vol. vi (1921), pp. 143-8

y. Min.

pp. 77-86.

¹ Wright, *Amer. J.* i. (4), vol. xxvi (1908), pp. 545-54 (Velardeña, Mexico).

constrained or metastable solid solution. The pleonaste of Scawt Hill contains 17 per cent. of the magnetite molecule, a much larger proportion than is normally held in any spinel mineral.¹ A comparable case is presented by certain highly aluminous augites, such as the fassaite of Monzoni, found in company with melilite and monticellite (Fig. 36. *B*). An alumina-percentage 10-12 or more distinguishes fassaite sharply from the ordinary pyroxenes of thermal metamorphism, which are commonly referable to the diopside type, though here more actual analyses are a desideratum.²

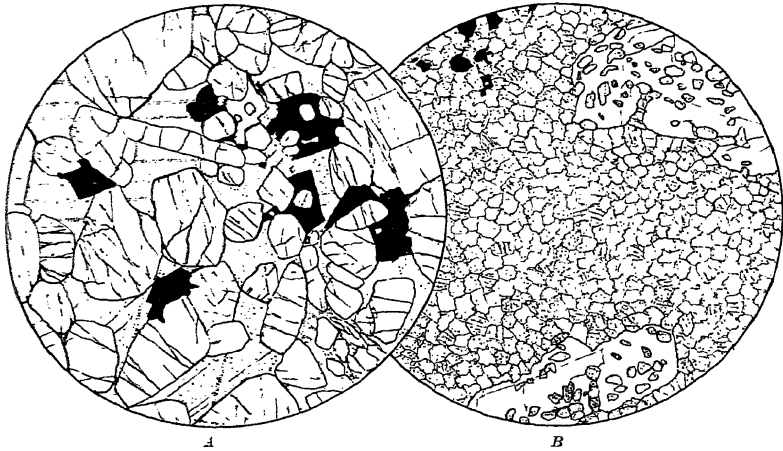


FIG. 37.—RARE MINERALS IN METAMORPHOSED CHALK at contact with dolerite, near Larne, Antrim; $\times 23$.

A. Spurrite with nearly opaque pleonaste and interstitial calcite.

B. Porphyroblasts of spurrite set in an aggregate of larnite and enclosing grains of the same; a little pleonaste.

GOLDSCHMIDT'S CLASSIFICATION OF TYPES OF HORNFELS

As an appendix to our discussion of metamorphism in sediments of various kinds, it will be useful to summarize very briefly Goldschmidt's classification of different types of 'hornfels' (p. 4), as since amplified by Tilley.³ It should be clearly understood, however, that such a scheme, concerned only with totally reconstructed rocks, which presumably represent final equilibrium associations of minerals,

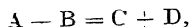
¹ Vogt, *Vidensk. Skr.*, 1910, No. 5, p. 9.

² In regional metamorphism pyroxenes rich in alumina may be stable in association with spinelled minerals and calcite, but not in presence of free silica; Tilley, *Geol. Mag.*, vol. lxxv (1938), pp. 81-5.

³ *Quart. Journ. Geol. Soc.*, vol. lxxx (1924), pp. 32-56; *Geol. Mag.*, vol. lx (1923), pp. 101-7, 410-18, and vol. lxii (1925), pp. 363-7.

throws no light on the course of metamorphism. The equations written down by Goldschmidt are not to be taken as representing actual reactions, but merely as expressing the relations between certain minerals in respect of composition.

Goldschmidt inquires what different associations of minerals, from a selected list, are possible in accordance with the Phase Rule. This is done by discussing relations (or conceivable balanced reactions) such as:



where the four letters stand for different mineral compounds. Here the possible associations are :

either AB, ABC, ABD,
or CD, ACD, BCD.

Which of the two sets of associations is to be adopted cannot be inferred theoretically, but must be determined by actual occurrences. For our purposes it will be sufficient to appeal directly to the petrographical evidence without following the steps of the argument, and the whole scheme can be conveniently presented in the form of a diagram.

It includes the various types of hornfels representing argillaceous and calcareo-argillaceous sediments; and the selected list of minerals is: andalusite (with sillimanite), cordierite, enstatite (and hypersthene¹), anorthite (with varieties of plagioclase), diopside, grossularite, and wollastonite. Quartz may also be supposed present, those rocks which are deficient in silica being reserved for later treatment. The inclusion of albite also makes no difficulty; but that orthoclase and the micas find no place is a serious departure of the ideal scheme from realities. Biotite is in fact present in all types except those rich in lime, and orthoclase often enters in addition.

The diagram (Fig. 38) shows the relations of the several types which contain free silica, the numbers corresponding with the different classes distinguished by Goldschmidt, as given in the list which follows. The inset numbers indicate limiting cases, implying some particular adjustment of the total chemical composition. The strictly non-calcareous rocks are covered by the first three types, two of which have been supplied by Tilley.

- (1) Andalusite, Cordierite.
 - (1A) Cordierite.
 - (1B) Cordierite, Enstatite.
- (2) Andalusite, Cordierite, Anorthite.
- (3) Cordierite, Anorthite.

¹In the diagram ferrous are understood to be included with

GOLDSCHMIDT'S

- (4) Cordierite, Anorthite, Enstatite.
- (5) Anorthite, Enstatite.
- (6) Anorthite, Enstatite, Diopside
- (7) Anorthite, Diopside.
- (8) Anorthite, Diopside, Grossularite.
- (9) Diopside, Grossularite.
- (10) Diopside, Grossularite, Wollastonite.

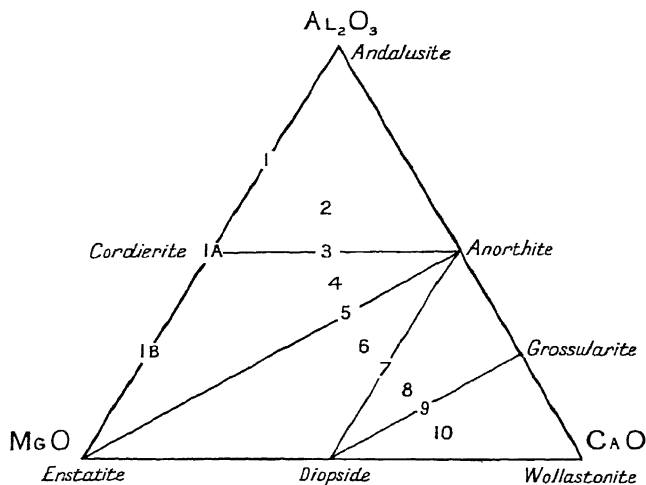


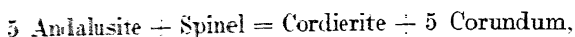
FIG. 38.—I SHOWING THE RELATIONS OF THE CLASSES OF HORNFELS
BY GOLDSCHMIDT.

In so far as the scheme is valid, the diagram exhibits clearly the manner in which the mineralogical constitution is determined by the total chemical composition. If we denote by A, M, C the relative proportions (in molecules) of alumina, magnesia, and lime, the conditions for the formation of the several minerals are seen to be as follows :

- | | |
|-------------------|---------------|
| for andalusite, | |
| for cordierite, | $A > C,$ |
| for diopside, | $A < C,$ |
| for enstatite, | $A + M > C,$ |
| and | $M + C > A,$ |
| for anorthite, | $C < 3A + M,$ |
| for wollastonite, | $C > 3A + M,$ |
| for grossularite, | $C > A + M.$ |

From these relations it would appear, e.g., that cordierite and diopside are necessary alternatives, in the sense that any hornfels of the kind in question must contain one of these minerals, and cannot contain both: and again (in lime-bearing hornfelses) wollastonite and anorthite (or some variety of plagioclase) figure as necessary alternatives. All such inferences, however, are subject to correction, having regard to the minerals biotite, orthoclase, and others, which are here ignored.

Coming now to the quartzless types, it is evident in the first place that, in any of the foregoing types, the amount of quartz may be supposed to dwindle to zero without disturbing equilibrium: this gives twelve limiting cases. If now we continue in imagination to abstract silica, it can come only from the breaking down of some silicate-mineral present, such as andalusite or cordierite. For these two minerals we have the relation:



and it appears that the stable associations are those which include cordierite and corundum.¹ So Tilley gives the following types, here numbered consecutively for convenience:

- (11) Andalusite, Cordierite, Corundum.
- (12) Cordierite, Corundum.
- (13) Cordierite, Corundum, Spinel.
- (14) Corundum, Spinel.

These may be regarded as the non-quartzose representatives of (1) corresponding with (1A) and (1B) we have in like manner:

- (15) Cordierite, Spinel.
- (16) Cordierite, Enstatite, Spinel.

Other types may be derived from (2) and (3):

- (17) Andalusite, Cordierite, Corundum, Anorthite.
- (18) Andalusite, Corundum, Anorthite.
- (19) Cordierite, Spinel, Anorthite.

To secure an artificial simplicity by disregarding minerals of inconvenient composition is a device already practised, in regard to igneous rocks, by the authors of the Quantitative Classification. Though patently a source of error, it may be justified in the present instance by the undoubted utility of Goldschmidt's manner of treatment and the lack of any alternative scheme.

¹ There are, however, records of the association andalusite-cordierite-spinel and even of the four phases together.

CHAPTER VIII

THERMAL METAMORPHISM OF IGNEOUS ROCKS

Special Features of Igneous Rocks—Thermal Metamorphism of Basic Rocks—Thermal Metamorphism of Deeply Weathered Rocks—Thermal Metamorphism of Acid Rocks.

SPECIAL FEATURES OF IGNEOUS ROCKS

IN respect of their behaviour in thermal metamorphism igneous rocks have hitherto received much less general notice than those of sedimentary origin. They present nevertheless some features of more than common interest, and to bring out the significance of these special features, rather than a comprehensive treatment of the subject as a whole, will be the aim of what here follows. Since thermal metamorphism is, in its most general aspect, merely a readjustment of the constitution of a rock to more or less high-temperature conditions, it may perhaps appear, upon a hasty judgment, that igneous rocks, themselves of high-temperature origin, will be little susceptible to changes of this kind. Such inference, while containing a certain measure of truth, fails, however, to take account of some important considerations.

In the first place, the genesis of an igneous rock, starting from a fluid magma and ending normally in a crystalline aggregate, covers a wide range of declining temperature, and the several constituent minerals, as we now see them, belong to different stages of the prolonged process of cooling. In many rocks the latest-formed minerals have crystallized at temperatures which may be overtaken in metamorphism of quite moderate grade. Further, we know that the consolidation of an igneous rock cannot, in the most general case, be truly pictured as a simple separation of the several minerals in turn from the fluid magma. Later minerals may be derived in part at the expense of earlier ones which, crystallized at a higher temperature, cease to be stable at a lower temperature in contact with the changed magma, and are attacked by it. To such reactions most petrologists, following Bowen,¹ assign an important part in the normal course of petrogenesis.

¹ The Reaction Principle in Petrogenesis, *Journ. Geol.*, vol. xxx (1922), pp. 177-98; *The Evolution of the Igneous Rocks* (1928), chap. v.

Whenever the early crystals of important minerals have not been removed or in some way protected from contact with the magma, they will often be liable to partial or total resorption at a later stage; but whether such reactions, demanded by chemical equilibrium, actually take effect or not will depend upon the conditions, and in particular upon the rate of cooling. In so far as any given igneous rock has actually passed through such changes with falling temperature, equilibrium being continually readjusted by the proper reactions, we may reasonably expect that the reactions will be reversed by rising temperature in thermal metamorphism.

If, on the other hand, owing to a too rapid rate of cooling or any other cause, these reactions making for equilibrium did *not* take effect as the magma cooled, some of the constituent minerals of the resulting rock must be in a metastable state. It cannot be doubted that a rock of such constitution will be eminently susceptible of thermal metamorphism. This is perhaps most clearly illustrated by considering an extreme case. If the rate of cooling be sufficiently rapid, crystallization is practically inoperative in the later stages, and the resulting rock consists partly of glass, which is essentially metastable. Now we know that, when such a glass is heated to a moderate temperature and so held for a time, devitrification is readily induced. Here crystallization, which is normally the result of cooling, appears as an effect of heating. It is an indirect effect, depending upon the fact that the higher temperature restores molecular mobility. Doubtless it also promotes atomic mobility; and we may confidently infer that change in the direction of equilibrium with falling temperature, such as the uralitization of pyroxene, having failed of effect in the first instance, may be precipitated when the rock is again to a suitable temperature in the course of thermal meta-

We are also prepared to find that a suspended reaction of this kind, made effective in a moderate grade of metamorphism, will be reversed in a higher grade.

An igneous rock, then, even when freshly consolidated, is not likely to be immune from change when subjected to any notable elevation of temperature. Besides this, few rocks that we meet with are in a perfectly fresh state. Owing to secondary changes, whether correctly described as weathering or not, there has usually been at least some production of low-temperature minerals such as kaolin, sericite, chlorite, serpentine, calcite, iron-oxides, etc. These are in fact the same substances that we have met with as the constituents of argillaceous and calcareous sediments. Here, however, they have not been distributed into separate deposits, but remain for the most

part in the rock in which they were generated. Some redistribution of the various secondary products within the rock is likely to be found, but it is as a rule narrowly limited. The process is a selective one, depending on relative solubility. Sericite and kaolin remain where they were produced, and so for the most part do serpentine and the iron-oxides. Epidote, chlorite, silica, and the zeolites are more liable to travel, and calcite, the most soluble of all, is also the most vagrant. These are the minerals commonly found in fissures, steam-vesicles, and other places of relief of pressure, the influence of pressure upon solubility being a controlling factor in the redistribution.

The earliest effects of thermal metamorphism in an igneous rock are shown by such low-temperature minerals, if any, as are present, including alteration-products of the kind just enumerated and sometimes the latest products of magmatic crystallization. Upon a moderate elevation of temperature these minerals readily undergo change, either individually or by reaction with one another. Incidentally there is an elimination of any oxygen or water or carbon dioxide taken up by the igneous rock in weathering or other destructive changes. Here we see in the successive reactions induced by rising temperature a *reversal* of those changes of the nature of degradation which affected the original rock with falling temperature (see p. 47). This principle, in which 'anamorphism' appears as the opposite of 'catamorphism', constituting the complementary part of a grand cycle of change, is applicable to thermal metamorphism in general, but it is in igneous rocks that it is most clearly exhibited. Here, since there has been no wide dispersal of the products of degradation, the new combinations which come from metamorphism are in general such as are familiar in pyrogenetic minerals, and the ultimate result is the restoration, as regards mineralogical constitution, of the original igneous rock. Some concrete examples will serve to set the matter in a clearer light.

THERMAL METAMORPHISM OF BASIC ROCKS

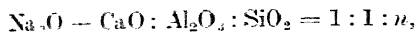
The amygdaloidal basalts of Tertiary age in Skye¹ and Mull² have in many places been metamorphosed by subsequent plutonic intrusions. In the non-metamorphosed basalts the contents of the amygdaloidal cavities may include chlorites, calcite, chalcedony, etc., but the principal and often the only minerals are lime- and soda-zeolites. Waiving for the moment the question of the precise mode of origin of these zeolites, we may conceive them as derived from plagioclase

¹ *The Tertiary Igneous Rocks of Skye* (Mem. Geol. Sur., 1904), pp. 50-3.

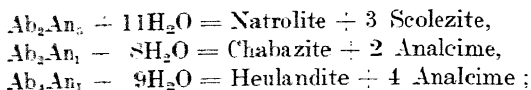
² *Tertiary and Post-Tertiary Geology of Mull, etc.* (Mem. Geol. Sur., 1924),

felspars by simple reactions involving hydration. We find accordingly that they are represented in the metamorphosed rocks by a crystalline aggregate of plagioclase feldspar, with or without other minerals.

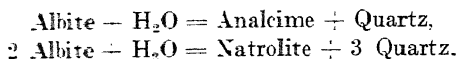
The general correspondence between the plagioclase group and the lime- and soda-zeolites is sufficiently apparent. In both we see the ratios (in molecules):



where n ranges from 2 to 6. There is not indeed a correspondence term by term. It is to be remarked, however, that the zeolites seldom occur singly but in associations of two or three species together. It is easy to devise such equations¹ as:



or, again, since free silica and other substances may accompany the zeolites:



Equations of this kind may well represent reversible reactions, which are driven towards the right with falling and towards the left with rising temperature.

This is, however, an incomplete view of the origin and metamorphism of the amygdales in these rocks, which present features of special interest. There is good evidence to show that in these basalts, and probably in many other amygdaloidal lavas, the minerals within the steam-vesicles are not secondary, but are the latest products of crystallization from a magma which had become rich in water and finally forced its way into the cavities. They are derived, not from the destruction of feldspar crystals, but from anorthite and albite molecules becoming hydrolysed in the aqueous magma. Further, the several minerals so found in association do not all belong to the same stage in the process of cooling, and later minerals have often been formed at the expense of earlier ones. They constitute in that case a 'reaction-series' as defined by Bowen. McLintock² has studied from this point of view the amygdaloidal basalts of the Ben More district of Mull and their metamorphism by subsequent intrusions

¹ I adopt here the text-book formulae for the various zeolites without inquiry concerning the significance of the contained water.

² *Trans. Roy. Soc. Edin.*, vol. lv (1915), pp. 1-33.

of granite. He makes it appear clearly that the reactions set up in metamorphism represent exactly the reversal of those which had taken place in the final stages of magmatic crystallization. The commonest zeolite in this district is scolecite, and this is the final term of a reaction-series which includes grossularite, epidote, and prehnite. In metamorphism the scolecite is first transformed to prehnite, this in turn to epidote, and so finally to grossularite.

Where basic rocks have suffered changes of the nature of weathering, calcite is a more or less abundant product; and the redistribution

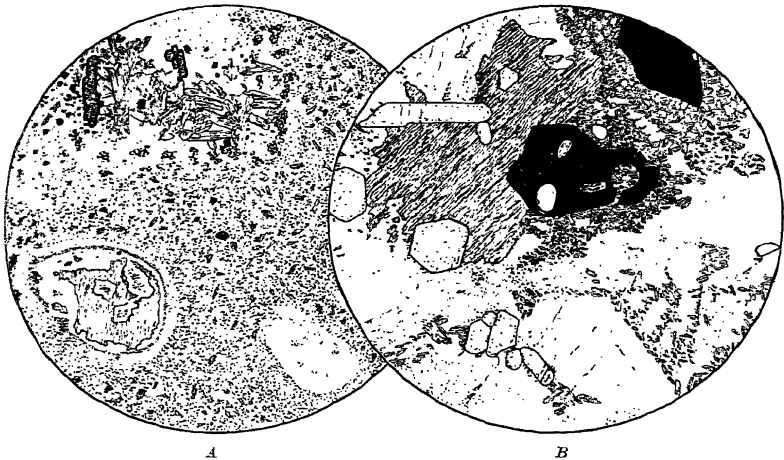


FIG. 39.—METAMORPHOSED IGNEOUS ROCKS; $\times 25$.

A. Amygdaloidal Pyroxene-Andesite, Wasdale Head, near the Shap granite, Westmorland. The only noticeable change in the body of the rock is the production of small flakes of biotite. The amygdales have a green hornblende instead, with some felspar and crystals of brown sphene: one at the bottom of the field is of quartz.

B. Gabbro metamorphosed by later acid intrusions, Caldbeck Fells, Cumberland. The gabbro is of a basic variety rich in apatite and iron-ore, which remain apparently intact. The augite is replaced by fibrous green hornblende with patches of brown biotite, the latter only in the neighbourhood of the iron-ore. The felspar has been cleared of its minute inclusions.

of this within the rocks, in virtue of its relatively free solubility, becomes an important factor influencing subsequent thermal metamorphism. The Ordovician lavas in the aureole of the Shap granite, Westmorland, afford very good illustrations.¹ The pyroxene-andesites on the west side of the granite were rocks not very rich in lime, and here calcite was mostly collected into the amygdales. In the general body of the andesite metamorphism has given rise to abundant

¹ Harker and Marr, *Quart. Journ. Geol. Soc.*, vol. xlvii (1891), pp. 292-301; vol. xlix (1893), pp. 359-65.

biotite, formed by reactions between chlorite, sericite, limonite, etc.; but in the amygdales we find especially lime-bearing minerals, chiefly a green hornblende but also epidote, sphene, etc. (Fig. 39, *A*). To the north of the granite were basaltic lavas much richer in lime, and here calcite had been produced more plentifully. It was generally disseminated, as well as gathered in vesicles and fissures. Accordingly, in the metamorphosed rocks green hornblende is of general occurrence instead of biotite. There were large amygdales, lines with chlorite and chalcedony and filled in with calcite; and here a number of

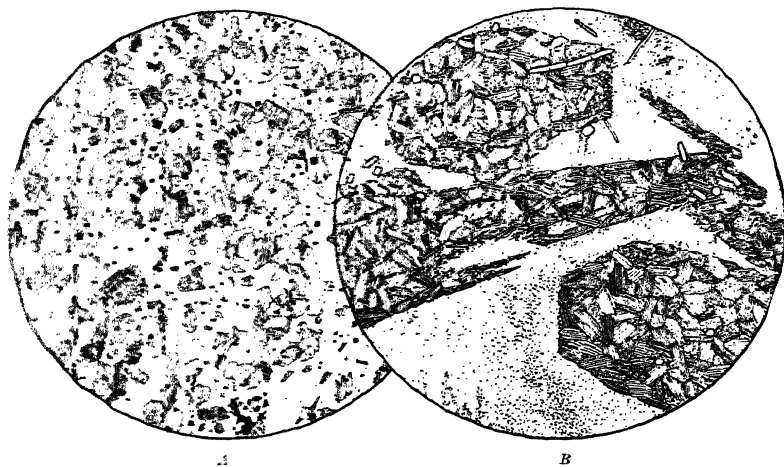


FIG. 40.—METAMORPHOSED IGNEOUS ROCKS; $\times 25$.

A. Basaltic Tuff:
The most conspicuous

B. Volcanic dyke
are replaced by ag-
and the apatite is

near the Shap granite, Longfell Gill, Westmorland.
are flakes of brown biotite and little octahedra of

granite, Catacol, Arnan. Well-shaped crystals of hornblende
of biotite. The felspar shows only the beginning of change,
hd.

silicates have been formed—epidote, green actinolitic augite, sphene, and large crystals of grossularite. In the centre of the largest amygdales is calcite, recrystallized without being too far from any source of silica to take part in chemical reactions.

tuffs, owing to their original finely clastic state and con- liability to weathering, are even more readily affected in thermal metamorphism than are lavas of like nature (Fig. 40, *A*).

So far we have discussed changes set up by metamorphism in the minor, and usually very late, minerals in igneous rocks. When,

however, a medium grade has been reached, the principal constituent minerals of the rock begin to be affected in their turn, either by reactions producing definite new minerals or at least by what is in appearance a mere recrystallization. The fabric of the rock necessarily suffers change at the same time, though larger structures, such as the porphyritic and amygdaloidal, may still persist. Here again it is the basic rocks which furnish the readiest illustrations.

The most constant and noticeable change in any gabbro, dolerite, or basalt which has reached a certain grade of metamorphism is the

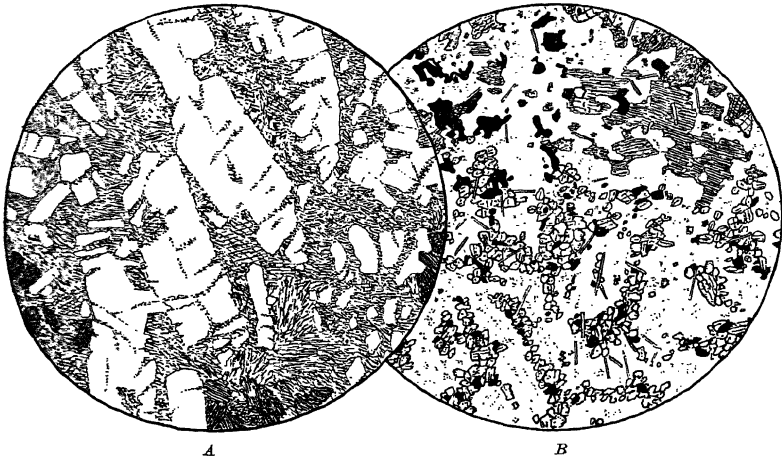


FIG. 41.—METAMORPHOSED DOLERITE DYKES, near the Granite of Beinn an Dubhaich, Skye; $\times 25$.

A. Kilechrist. The ophitic augite is replaced by an aggregate of green hornblende, with a few little patches of biotite. The felspar is cleared of its inclusions, but not recrystallized. Narrow veinlets of hornblende traversing the clear crystals represent cracks which had been occupied by chlorite.

B. Torran. This dyke is enveloped in the granite, and shows a higher grade of metamorphism. Hornblende is seen in the upper part of the field, but has given place elsewhere to granules of new augite. The felspar and magnetite (but not the apatite needle) are recrystallized, and the original structure of the rock is only faintly suggested.

conversion of the augite to hornblende, commonly of a light green variety (Figs. 39, *B*; 41, *A*). As first formed, it makes distinct pseudomorphs. Hornblende may arise too from decomposition-products of augite, and this can often be distinguished by its manner of occurrence, e.g. as slender strings occupying cracks in the felspar. Rhombic as well as monoclinic pyroxene suffers uralitization, and even bastite pseudomorphs after hypersthene are converted to a pale green amphibole.¹ Closely associated with hornblende, as if taking its

¹ Harker, *Quart. Journ. Geol. Soc.*, vol. 1 (1894), p. 332 (Carrock Fell, Cumberland).

place, patches of deep brown biotite are not infrequently seen, and they usually occur about crystals of primary magnetite. What is here especially worthy of remark is the conversion of a higher mineral (pyroxene) to a lower (amphibole) as an incident of thermal metamorphism. This behaviour, at first sight anomalous, finds an explanation in considerations already noted (p. 102). It is a deferred or suspended reaction, which now takes effect when the appropriate temperature is realized.

The pyroxene and the replacing hornblende differing in composition, the transformation cannot be regarded as simple paragonism. In general the reaction must involve also other minerals, though these may be merely minor constituents, such as magnetite, secondary chlorite, serpentine, etc. A case of special interest is that of eclogite enveloped in a granitic intrusion and thermally metamorphosed.¹ Here, as will be noted later, the pyroxene is of a peculiar kind, containing the elements of plagioclase feldspar as part of its constitution. Both it and the associated garnet, rich in the pyrope molecule, are high-pressure minerals not stable under ordinary conditions; and amphibolization in this case is to be regarded as a reaction between the two minerals. It produces not only hornblende but plagioclase.

Any appreciable recrystallization of the feldspar of an ordinary basic rock comes later than the uralitization of the pyroxene, but certain changes due to metamorphism may be developed at an earlier stage. The phenomena are not always the same. Often the dull feldspar crystals are seen to become quite pellucid, an effect probably to be ascribed to the absorption of very minute inclusions of such minerals as zoisite and sericite (Figs. 41, 42). On the other hand there are numerous observations of relatively clear plagioclase, especially of the more calcic varieties, acquiring a peculiar cloudiness as a result of thermal metamorphism.² This is due to the development of a multitude of very minute opaque inclusions (Fig. 40, *B*). In some instances there has been a formation of magnetite from an original content of iron-oxide in the feldspar, in other cases perhaps a development of secondary glass-inclusions. It seems that the subject is one which calls for further investigation. When recrystallization of the feldspar sets in, the crystals may not at first lose their individuality in the process, and phenocrysts or the scattered crystals in a tuff may or may not be replaced by a granular mosaic. With advancing metamorphism, however, original outlines are lost, and the whole rock

Vidensk. Skr., 1921, No. 8.

gor. *Min. Mag.*, vol. xxii (1931), pp. 524-38. See also Miss G. A. Proc. *Linn. Soc., N.S.W.*, vol. lviii (1933), pp. 152-6.

takes on a crystalloblastic type of structure. Since various chemical reactions are in-progress, it is not to be assumed that recrystallization, whether of feldspar or of other minerals, leaves their original composition unchanged.

Magnetite and ilmenite of primary origin have often furnished a certain amount of iron and titanium for the formation of biotite at a somewhat early stage, but a general recrystallization of the iron-ores belongs to a higher grade, following the stage of uralitization. It is still later, if at all, that olivine is affected. At a sufficiently high

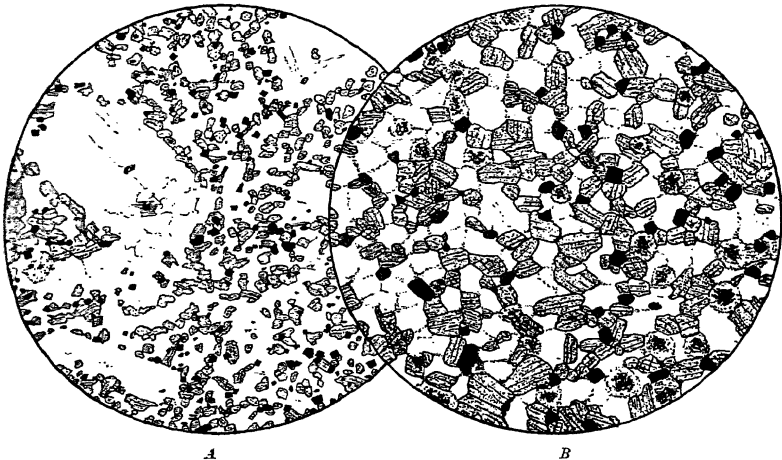


FIG. 42.—HIGHLY METAMORPHOSED BASALT LAVAS, enveloped by gabbro intrusion, Skye; $\times 25$.

A. Harta Coire. B. Druum an Eighne. Metamorphism of a high grade has restored the original mineralogical composition (augite, plagioclase, magnetite) but with a crystalloblastic structure. The former figure still shows large porphyritic feldspars, usually recrystallized as single individuals, but the one on the left partly replaced by a granular mosaic. B is the 'granulitic gabbro' of Geikie and Teall: see *Quart. Journ. Geol. Soc.*, vol. I (1894), p. 647, and Harker, *Tertiary Igneous Rocks of Skye* (1904), p. 115.

temperature it may become recrystallized; but newly formed olivine may also be found with a manner of occurrence suggesting its formation from serpentine and other alteration-products.¹ Apatite often shows no sign of change even in very highly metamorphosed rocks (Fig. 39, B). Broadly speaking, the several constituents of the rock yield to metamorphism in an order the reverse of that in which they originally formed from the magma. Ilmenite has sometimes survived metamorphism of the most drastic kind, and the zircon, which is an occasional constituent of gabbroitic rocks, always remains intact.

¹ MacGregor, *Geol. Mag.*, vol. lxxviii (1931), p. 508.

The highest grade of metamorphism in ordinary basic igneous rocks is marked by the total obliteration of all original structures except those of a large order such as the amygdaloidal. Mineralogically the most notable feature is the reappearance of augite, which now becomes the normal and stable ferro-magnesian constituent (Figs. 41, *B*; 42). The unalutization effected at an earlier stage is thus reversed, and hornblende formed by other reactions, e.g. in the interior of amygdales, likewise gives place now to augite (Fig. 43, *A*). The new augite has not necessarily the same composition as that of the

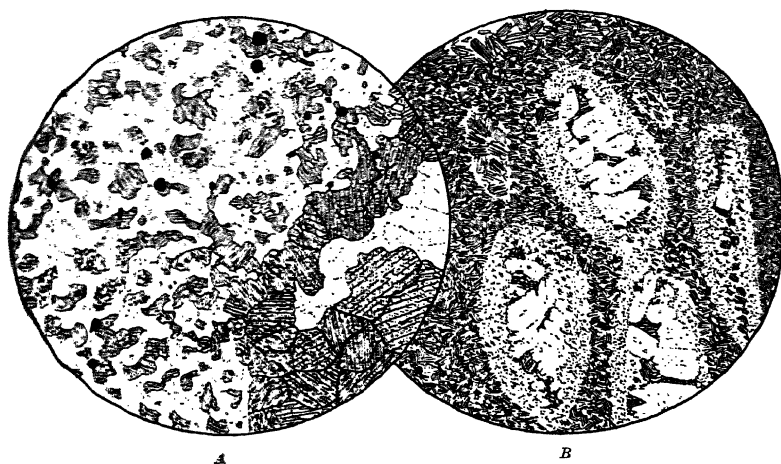


FIG. 43.—HIGHLY METAMORPHOSED AMYGDALOIDAL LAVAS; $\times 25$.

- A*. Basalt near the peridotite of An Sgùman, Skye. Totally recrystallized, showing, e.g. feldspar, magnetite, and pseudomorphs after olivine. On the right is part of an amygdale, occupied formerly by chlorite and zeolites, now by augite and feldspar.
- B*. Pyroxene-Andesite, Wasdale Pike, near the Shap granite, Westmorland. The rock had suffered from weathering prior to metamorphism. Abundant flakes of biotite are the most prominent constituent, together with new feldspar. The large crystals within the amygdale are of labradorite.

rock, and it may be accompanied by hypersthene. Enclosed within amygdales of basic rocks with 'granulitic' structure are of frequent occurrence in the Tertiary gabbros and eucrites of Skye, Mull, and Ardnamurchan. Sometimes they represent basalt lavas (Fig. 42 *B*); but often they seem to come from the reconstruction of older (and more basic) intrusive rocks, belonging to the same series as the mass.¹ When an allivalite or felspathic eucrite has been

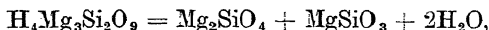
¹ *Tertiary and Post-Tertiary Geology of Mull* (Mem. Geol. Sur. Scot., 1924), pp. 252-3; *Geol. of Ardnamurchan* (Mem. Geol. Sur. Scot. 1930), pp. 229-32, 308.

thus metamorphized, a dark green spinellid (pleonaste) is sometimes a conspicuous new product.¹

THERMAL METAMORPHISM OF DEEPLY WEATHERED ROCKS

It has been shown that low-temperature alteration-products disseminated through an igneous rock are eminently susceptible to change in thermal metamorphism. More striking are the effects produced when igneous rocks which have been *deeply weathered throughout* are involved in a metamorphic aureole. Here again it is among basic and ultrabasic rocks that we find the most remarkable examples.

In serpentine we have an instance of a rock composed almost wholly of secondary minerals. Although the hydration and other changes which convert olivine and pyroxene to serpentine may not be correctly ascribed to atmospheric weathering, they are obviously of a kind which we may expect to be reversed by high temperature. It is found in fact that serpentine fused in a crucible recrystallizes as a mixture of olivine and enstatite :



but what elevation of temperature this reaction demands we are not informed. We cannot cite examples of peridotites which have certainly come from the metamorphism of serpentine-rocks, but some occurrences in the Eastern Alps possibly fall under this head.

The chief products from the destructive weathering of ordinary basic rocks are calcite and chlorite. If the abundant calcite remains in the rock, subsequent metamorphism follows the same general lines as in an impure limestone, giving rise to such minerals as grossularite, idocrase, and diopside. Often there has been some redistribution of the calcite within the rock, and this is especially true where there has been crushing and shearing, setting up a banded arrangement. Good examples are furnished by the Devonian spilitic lavas on the western border of the Dartmoor granite.² Some of these rocks are now composed mainly of green hornblende and lime-garnet, disposed in alternating parallel streaks. Other minerals which enter are epidote and zoisite, diopside, and some biotite.

Under other conditions basic igneous rocks may suffer weathering of a more drastic kind, the resulting calcite being more or less completely removed, while other constituents besides lime may also suffer reduction. The proportions of the more stable constituents are thus automatically raised, even when there is no actual accession of material.

¹ *Geol. of Ardnamurchan*, p. 317, with figure.

² *Geology of Dartmoor (Mem. Geol. Sur. Eng. and Wales, 1912)*, pp. 20-3, plate II, fig. 4.

Quantitative estimates of the addition and subtraction of the various oxides involve an element of uncertainty: for it is not safe to assume that a particular constituent, such as alumina, remains unchanged, and the alternative assumption of no change of total volume rests on no assured grounds.

The migration of dissolved material *within* a rock-mass subjected to destructive weathering may bring about some concentration of certain constituents in particular places: but this process is probably much more effective as an incident of metamorphism in the vicinity of a plutonic intrusion, heated water furnished by the magma serving as solvent and carrier (see below, p. 115).

THERMAL METAMORPHISM OF ACID ROCKS

The basic igneous rocks have been treated at some length, because it is in these that the principles enunciated at the outset are most clearly illustrated. The *acid rocks* and those composed largely of alkali-felspars may be dismissed more summarily, except in so far as they introduce new points of interest. There are certain types consisting essentially of felspars and quartz, and it is evident that here no far-reaching chemical reactions are to be expected. At first there may be only mechanical effects, such as the shattering of the larger quartz-grains in a granite, a consequence of unequal expansion. In a sufficiently advanced grade felspar and quartz become, at least in part, recrystallized, with some tendency to a graphic intergrowth of the two minerals. The rhyolites or devitrified obsidians of Ordovician age in Westmorland are transformed near the Shap granite to a granular mosaic of felspar and quartz. A few scattered flakes of brown and white micas represent chloritic and sericitic material in the original lavas.

Among the ferro-magnesian minerals a very characteristic change is the replacement of hornblende by biotite, in an aggregate of flakes making a pseudomorph (Figs. 40, *B*; 45, *A*). This is clearly a deferred reaction analogous to the conversion of augite to hornblende, for Bowen's 'reaction-series' pyroxene-amphibole-biotite may be regarded as the normal course in magmas rich in potash. So also, to complete the parallel, a high grade of metamorphism reverses the reactions. Both hornblende and biotite are destroyed, giving rise to granular augite, accompanied in the case of biotite by much finely divided magnetite. These and other points are well illustrated by the granites and granite-gneisses of British Guiana,¹ where they are intersected by massive dykes of quartz-dolerite (Fig. 44).

¹ Harrison. *The Geology of the Goldfields of British Guiana* (1908), pp. 36-7, 7, etc.

In conclusion, something should be said of *xenoliths*—i.e. inclusions of relatively small dimensions—of one igneous rock in another later one.¹ These have naturally suffered thermal metamorphism after their kind. The *grade* of metamorphism, depending on the highest temperature attained, is determined by the nature of the enveloping rock, more basic magmas being intruded or extruded at higher temperatures than more acid ones. So, for example, a granite xenolith enclosed in a quartz-porphphyry shows hornblende converted to biotite (g. 45); while a similar xenolith enclosed in a basalt has its horn-

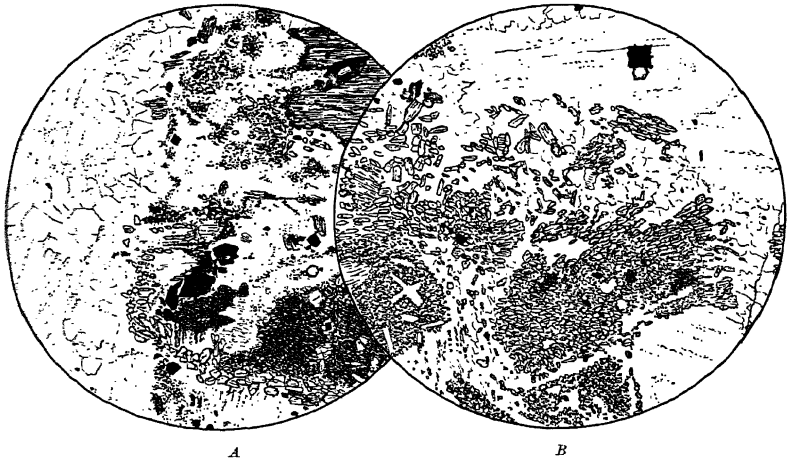


FIG. 44.—GRANITES METAMORPHOSED in the vicinity of great dykes of dolerite, British Guiana; $\times 23$.

A. Biotite-Granite, Tinamu Falls of Cuyuni River. Flakes of biotite are partly or wholly replaced by magnetite dust and granules of augite. The quartz has been shattered.

B. Hornblende-Granite, Great Falls of Demerara River. The hornblende is completely replaced by granular augite. Some part of the felspar and quartz has been recrystallized with a rude graphic intergrowth.

blende replaced by augite and its biotite by augite and magnetite. Often, and especially in a case like the latter, there is some mechanical breaking up of the xenolith and dispersal through the matrix. This facilitates further reactions, involving an actual interchange of substance between xenolith and matrix. The production in this way of heterogeneous and hybrid rocks makes an interesting study, but to pursue it would carry us beyond the limits of our present subject.

¹ There is an extensive literature of xenoliths. See especially Lacroix, *Les Enclaves des Roches Volcaniques* (Macon, 1893) and numerous later writings of the same author.

The circumstances may be such that, after a high temperature has been reached, cooling is comparatively rapid. This is especially likely to befall xenoliths in a volcanic rock, and accordingly these often show the effects of *local fusion and vitrification*. The case is comparable in a general sense with that of the 'spotted slates' (p. 15); but the centres of local fusion, instead of being scattered fortuitously through the mass, are here determined by the particular minerals present. In a granite xenolith biotite is the mineral most easily affected. It yields a brown glass enclosing minute crystals of pleonaste,

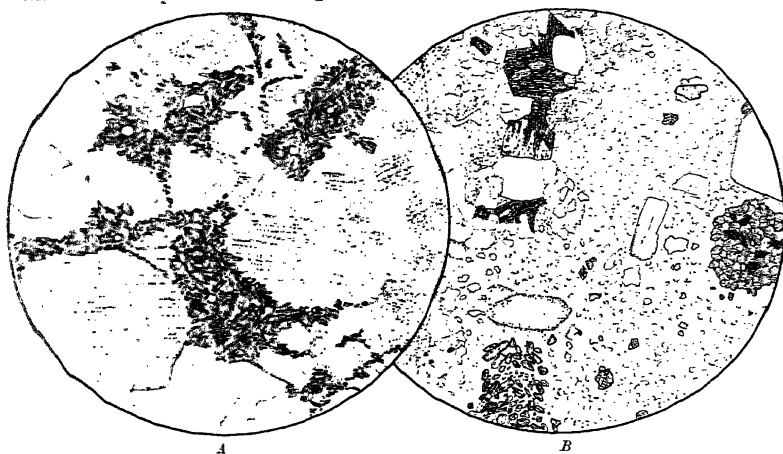


FIG. 45.—XENOLITH OF HORNBLENDE-GRANITE IN QUARTZ-PORPHYRY, Carrick Broad, Dundalk; $\times 23$.

A. Shows replacement of hornblende by biotite. Strings of chloritic alterations are replaced in the same way.

B. The same replacement is seen, with some small relics of hornblende; but detached fragments, enveloped by the quartz-porphyr magma, have given instead a new crystalline body of hornblende.

e. sillimanite, or sometimes hypersthene. The feldspars in the xenolith may be still intact, except that cleavage-cracks have been opened and secondary glass-inclusions developed. In the extreme case, however, a xenolith may be wholly fused, with the exception of such refractory minerals as zircon. This is a condition eminently favourable to intermingling of material with the surrounding magma.

We have tacitly disregarded the effects of *pressure* in the metamorphic rocks, although under deep-seated conditions this certainly not negligible. Its influence is shown in promoting the formation of such minerals as pyroxenes, garnet, sphene, etc., in Law. This subject, however, will be more treated under the head of regional metamorphism.

CHAPTER IX

PNEUMATOLYSIS AND METASOMATISM IN THERMAL METAMORPHISM

Pneumatolysis Superposed on Metamorphism—Introduction of Borates—Introduction of Fluorides and Chlorides—Introduction of Sulphides and Iron Compounds—Introduction of Soda—Other Metasomatic Changes.

PNEUMATOLYSIS SUPERPOSED ON METAMORPHISM

IN the thermal metamorphism of various sedimentary and igneous rocks, as hitherto considered, the chemical reactions involved practically no material other than that furnished by the composition of the rocks themselves. From the igneous intrusion which was regarded as the cause of the metamorphism nothing was demanded beyond heat, and sometimes perhaps a modicum of water in supplement of that already present. In fact, however, it is often found that the rocks adjacent to an intrusion have been invaded by emanations from that source, which included in sensible quantity, not only water, but other volatile bodies chemically more active. These have entered into energetic reaction with the material of the rocks, as is often proved by the incorporation of one or other of these active substances in the final products. Chief among the bodies which play this part are borates, fluorides, and chlorides. At a sufficiently elevated temperature they are in the gaseous state, and this is implied in the term *pneumatolytic* as describing their chemical action.

It is not an arbitrary refinement that discriminates between the chemical action of water and the more restricted but more potent action of its associates. While the ubiquitous water officiates at every stage of metamorphism, the other volatile bodies, besides being restricted in range, become important only when a certain 'pneumatolytic phase' is reached. This phase is often clearly indicated in the igneous rock itself, and is marked there as one of the latest episodes. The volatile constituents made part of the magma from the beginning, and assisted as fluxes and mineralizers throughout its crystallization. Only towards the close of that process, when the temperature had greatly declined, did the same substances begin to exercise a destructive effect upon minerals already crystallized. It was especially at this

late stage that the volatile bodies, now liberated as gases, were able to escape into the surrounding rocks. Thermal metamorphism proper must clearly be assigned in the main to an earlier time, when the temperatures were higher, and we conclude that in general *pneumatolysis follows metamorphism, and is superposed upon it*. The geological evidence of this is convincing. It can often be verified that rocks have been jointed, brecciated, or faulted in the interval between metamorphism proper and pneumatolytic changes. Again, we see that characteristic structures of metamorphism, such as certain types of spotting in slates, were in existence before pneumatolysis supervened and wrought new changes. On the other hand, if this later action be of an energetic kind, all recognizable traces of the preceding metamorphism may be lost in a general reconstruction of the rock. The term *pneumatolytic metamorphism* is then a convenient one as embracing the final results of the two processes when they are not clearly

all plutonic intrusions are attended by important emanations of gases. The generally accepted scheme of the evolution of different plutonic rocks, in an order of decreasing basicity and increasing alkalinity, involves also a progressive enrichment of the later derivatives in volatile constituents. It is in accordance with this that granites and nepheline-syenites are much more generally attended by important pneumatolytic effects than are rocks of more basic and calcic nature. The rule which would associate borates and fluorides especially with the former rocks and chlorides with the latter has no more than a loose and general validity.

While the minerals produced in simple thermal metamorphism draw their material solely from the substance of the rock metamorphosed, pneumatolysis introduces an extraneous element in addition. The composition of the new minerals, or of some of them, depends now upon two factors, which are quite independent. The second element, though it may be quantitatively much inferior, sets an unmistakable stamp on the whole, since without it the most distinctive minerals could not be formed. For this reason it will be convenient to arrange our observations, not primarily according to the original nature of the rocks affected, but with reference to the particular pneumatolytic agent involved.

INTRODUCTION OF BORATES

The most widespread type of pneumatolysis associated with granitic intrusions is due to *boric emanations*, and takes the form especially of *tourmalinization*. The characteristic mineral *tourmaline* is a boro-

silicate of the type $R_7B_3(Al_3Si_8O_{27})(O.OH)_4$, in which the principal base is alumina, while ferrous oxide, magnesia, soda, manganous oxide, lime, etc., are present in varying proportions. Analyses show that the colourless and red varieties are highly aluminous and contain little iron or manganese; the common yellow-brown kind has lower alumina and is rich in iron; while blue colours are probably related to a noteworthy content of soda, and are much less common in metamorphosed rocks than in granites. A mineral so rich in alumina (35 to 40 per cent.) is naturally associated especially with argillaceous sediments.

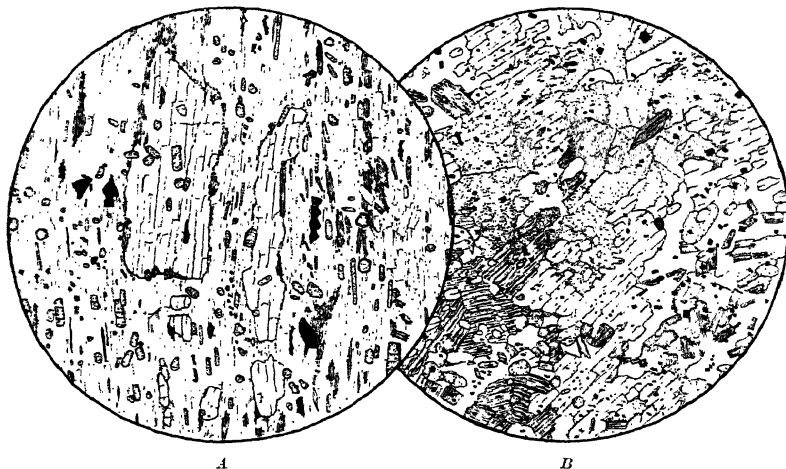


FIG. 46.—TOURMALINIZATION OF METAMORPHOSED SLATES, Cornwall; $\times 23$.

A. Andalusite-Mica-schist, near the Bodmin Moor granite, Blisland. Showing numerous little crystals of tourmaline. These are mainly derived from biotite, but the andalusite is also beginning to be attacked. The abundance of white mica is doubtless another effect of pneumatolysis.

B. Xenolith of andalusite biotite-hornfels enclosed in the St. Austell granite. Showing a more extensive production of tourmaline from both biotite and andalusite. Part of the quartz is a by-product of the same transformation.

The Devonian slates near the granites of Cornwall and Dartmoor afford abundant material for study.

The rocks, being already metamorphosed and often in the state of dense compact hornfels, were not very freely permeable by gases. Tourmalinization may indeed be found at a considerable distance from a granite-contact, but only in proximity to tourmaline-quartz-veins, which mark the channels of supply. The change commonly begins with the formation of little crystals of tourmaline, enclosed in those aluminous silicates which could furnish most of the material.

Biotite is first attacked, then cordierite and andalusite, and finally feldspar if present. As the process goes on, the gradual replacement by tourmaline of the various minerals of metamorphism is very evident (Fig. 46). It does not, as a rule, yield sharply defined pseudomorphs, and it is clear that there is considerable freedom of diffusion within the rock—appreciably more than is possible in ordinary thermal metamorphism. Yellow-brown tourmaline, undoubtedly an iron-bearing variety, is seen replacing andalusite as well as biotite. The tourmaline, moreover, tends constantly to develop its proper crystal

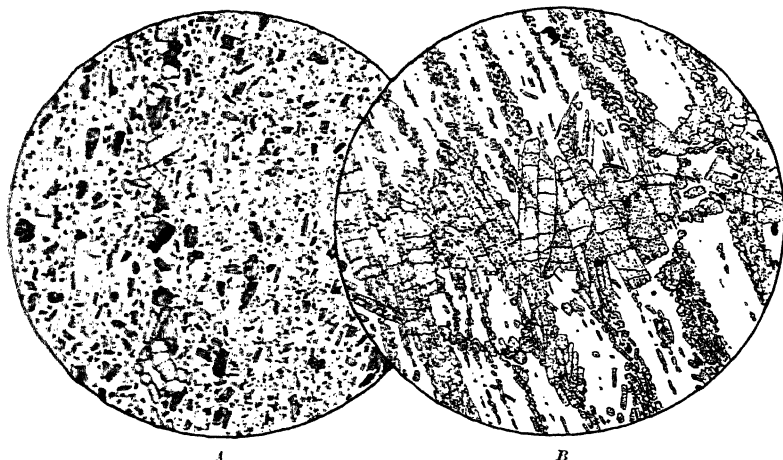


FIG. 47.—STAGES OF TOURMALINIZATION, in rocks bordering the St. Austell granite, Cornwall; $\times 25$.

A. The earliest stage: a muscovite-biotite-hornfels from Dennis, showing the formation of crystals of tourmaline at the expense of biotite. They occur along a line, which marks the fissure by which the gases found entrance.

B. The final stage: a tourmaline-quartz-schist from Roche. The fissure of supply is still indicated by a belt of larger crystals crossing the bands.

e, and sometimes shows a zony distribution of colours, though this is much less common here than in tourmalinized granites.

Ultimately all the silicates are destroyed, and the final product of boric pneumatolysis in a slate, as in a granite, is a tourmaline-quartz-rock. Here, however, it may be named a tourmaline-quartz-schist, for the little prisms of tourmaline have a common orientation, and are crowded along particular bands (Figs. 47 B; 48 A). This

of old structures shows that the replacement has been wholly by molecular and atomic processes. In this last stage, as in the earliest, the fissure by which the gases found access can often

be identified (Fig. 47, *B*). Quartz is abundant in many of these rocks. It comes in part from the formation of tourmaline at the expense of less basic silicates, in part from the recrystallization of quartz contained in the hornfels: but it is evident that there has often been also an introduction of new silica.

The chemical reactions here implied are clearly of a very drastic kind. Whether there has been any addition of substance, other than boric acid and silica, it is not easy to pronounce¹; but some removal, of potash at least, must be assumed. More knowledge is required for

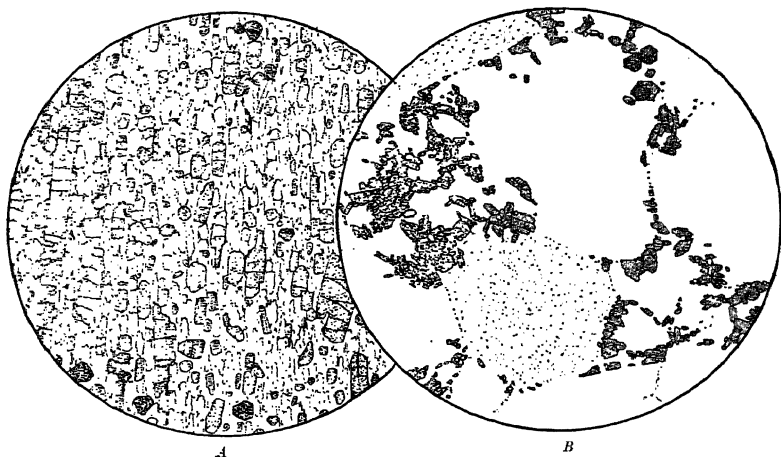


FIG. 48.—TOURMALINIZED ROCKS; $\times 25$.

A. Tourmaline-quartz-schist, enclosed in the Foxdale granite, Isle of Man. The parallel arrangement of the tourmaline crystals is well shown.

B. Tourmalinized grit, Cwm Dwythwe, near Snowdon. The elastic quartz is in part recrystallized, but the tourmaline is mainly confined to the interstices between the grains.

a full understanding of the chemistry of tourmalinization; but it is probable that it is due only in part to pneumatolysis in the strict sense. The first formation of tourmaline in the rock may demand little more than an accession of boric acid or some volatile borate. The total reconstruction, which may or may not follow, is perhaps to be assigned to a somewhat later phase of igneous activity and to the agency of liquid solutions, to which are also attributable the associated tourmaline-quartz-veins. In confirmation of this we have the fact that tourmaline has sometimes been formed in a quartzose grit² or a

¹ Most analyses of tourmaline, however, show a small proportion of fluorine.

² Fearnside's, *Rep. Brit. Assoc. for 1908 (1909)*, p. 704; Williams, *Quart. Journ. Geol. Soc.*, vol. lxxxiii (1927), pp. 354-6 (basal Ordovician grits of the Snowdon district).

limestone at a distance from any igneous intrusion (Fig. 48. *B*). This, it would seem, is to be explained only by the bodily introduction of tourmaline, or at least of the sum-total of its constituents in some form.

The common boron-mineral in calcareous rocks is *axinite*. This is essentially a borosilicate of calcium, $\text{HCa}_2\text{Al}_2\text{B}(\text{SiO}_4)_4$, though iron, and magnesium may also enter. Like tourmaline, it is in evident relation with fissures in the rocks, but it has a more red distribution. Good localities are Tregullan, on the northern

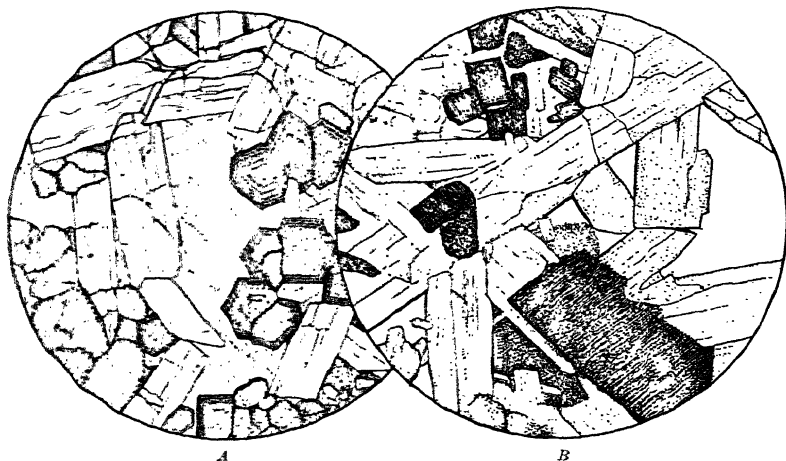


FIG. 49.—AXINITE-BEARING ROCKS, Tregullan, S. of Bodmin, Cornwall; $\times 25$.

A. Axinite-Andradite-Calcite-rock.

B. Axinite-Hedenbergite-Q.

That the garnet and pyroxene of these rocks are of varieties rich in iron is doubtless due to a metasomatic change of the kind described later as characteristic of many lime-

of the St. Austell granite,¹ and Ivybridge and South Brent, on the fringe of Dartmoor.² The common associates of axinite are andradite and hedenbergite (Fig. 49), sometimes also epidote and actinolite, and rarely some tourmaline. Axinite is produced, not only in calcareous sediments, but often also in basic igneous rocks, which have been metamorphosed within a granite-aureole (compare Fig. 5, *A*, above). Such rocks may have suffered alteration, with formation of calcite, prior to metamorphism. In them, as well as in lime-silicate-rocks, it is not uncommon to find slender veins or strings of axinite, doubtless representing calcite veins. A much rarer mineral, with

and Thomas, *Min. Mag.*, vol. xv (1908), pp.

² Busz, *Neu. Jb. Min.*, Beil. Bd. xiii (1900), pp. 125-32.

the same association as axinite, is datolite, $\text{Ca}(\text{BOH})\text{SiO}_4$. It is recorded by Busz at South Brent in Devonshire.

INTRODUCTION OF FLUORIDES AND CHLORIDES

In argillaceous rocks pneumatolytic metamorphism by the agency of *fluorides* is less prominently in evidence than that due to borates, but it plays a part by no means negligible. In plutonic rocks themselves, such as the Cornish granites, greisenization represents an action no less energetic than extreme tourmalinization, but its operation is more restricted. Topaz, so highly characteristic of the greisens, does not figure in metamorphosed sediments, except in injection-veins at an actual contact. The more easily transported fluor has a wider distribution of the same kind, but its relation to any particular intrusion is not always evident. The most usual repository of fluorides introduced into metamorphosed slate-rocks is to be seen in the *white micas* which have often been developed abundantly in the vicinity of a granite or greisen. The production of white mica at the expense of such minerals as feldspar, andalusite, and cordierite is a reversal of the processes by which those minerals were built up in thermal metamorphism, and points clearly to the intervention of a different factor. It is to be observed especially in the inner aureoles of muscovite-bearing granites, such as those of Cornwall, Dartmoor, Skiddaw, and Leinster.

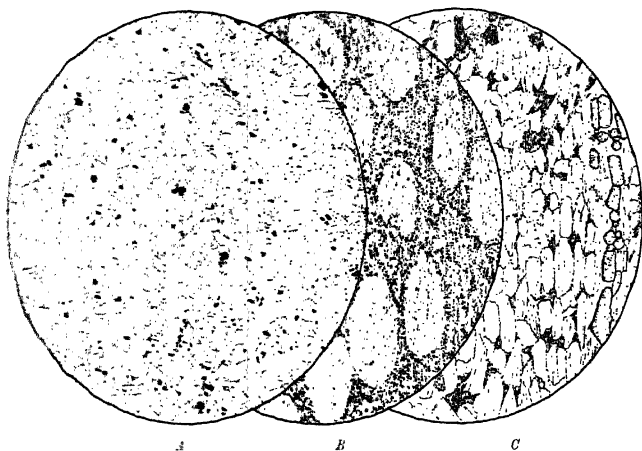
It is to be regretted that we possess little knowledge concerning the nature of micas occurring in this manner, and more particularly their content of fluorine. Muscovite is found, sometimes in great abundance (Figs. 46, *A*, 50, *C*); but more commonly the little flakes show the lower refractive index and weaker birefringence which are the properties of *lepidolite*, and may be provisionally distinguished by that name. The lepidolite of the mineralogists contains 5 per cent. or more of fluorine, with 4 or 5 per cent. of lithia, and has silica nearly in the metasilicate ratio. Whether our mineral can be identified with this must, however, remain a doubtful question. Often the flakes are so woven into the texture of a hornfels that their formation must have been part of a total reconstruction of the rock (Fig. 50, *A*). In other cases the structures of thermal metamorphism are only partly obliterated, and the mica—usually in very fine scales—can be seen replacing the crystals of cordierite, etc. The magnesia of cordierite and biotite gives rise to chlorite, mingled with the mica (Fig. 50, *B*).

The not infrequent occurrence of abundant white mica in metamorphosed slates which are also partly tourmalinized may be taken to indicate the joint action of fluorides and borates. Muscovite-tour-

PNEUMATOLYSIS AND METASOMATISM

schists appear to be not uncommon in the Land's End district of Cornwall.

It is, however, in those metamorphosed rocks which represent impure dolomites and magnesian limestones that the presence of fluorine most often reveals itself by the occurrence of distinctive minerals. The most widespread of these is the mica *phlogopite*. The variety has, according to Clarke, the ideal composition $H_2KMg_3AlSiO_4$, with partial replacement of H by MgF, while yellow and brown colours indicate some content of iron.² The fluorine



G. 50.—METAMORPHOSED SLATES RICH IN WHITE MICA; $\times 23$.

A. Lepidolite-Hornfels, close to the gneiss of Grainsgill, Cumberland: composed of chlorite and chlorite with some quartz and pyrites.

B. Pneumatolytically altered cordierite-mica-schist, near Bodmin, Cornwall: now consisting of lepidolite and chlorite, with a little quartz. The original schistose structure is not lost.

C. Muscovite-schist, twenty feet from granite, Warleggon, Cornwall: mainly of muscovite with biotite and quartz; on the right a string of crystals of brown tourmaline.

may amount to as much as 4 or 5 per cent. Phlogopite is found in flakes scattered through a marble or as one among other minerals in a lime silicate rock (Figs. 51, A. 52). An interesting group of magnesian fluosilicates is that which includes *chondrodite*, *humite*, and *clinohumite*. Only the first of these is a common mineral, and the last is rare. the composition of the three minerals:

Chondrodite, $Mg_3(MgF)_2(SiO_4)_2$;

Humite, $Mg_3(MgF)_3(SiO_4)_3$;

Clinohumite, $Mg_2(MgF)_2(SiO_4)_4$;

² *Geol. Land's End (M. Geol. Sur., 1907), p. 26.*

formula

with replacement of OH by

we may regard them as arising from the union of one molecule of magnesium fluoride with two, three, and four molecules of forsterite, respectively. This does not, of course, assume that the fluorine entered the rock in the form of magnesium fluoride. A frequent associate both of phlogopite and of chondrodite is a blue or green *fluor-apatite*. The ideal compound $\text{Ca}_4(\text{CaF})(\text{PO}_4)_3$ carries 3.8 per cent. of fluorine, but some part of this may be replaced by chlorine.

The calcium fluosilicates are rare minerals. Of these *cuspidine* has probably the formula $\text{Ca}_4\text{Si}_2\text{O}_7\text{F}_2$, while in *custertite* part of the

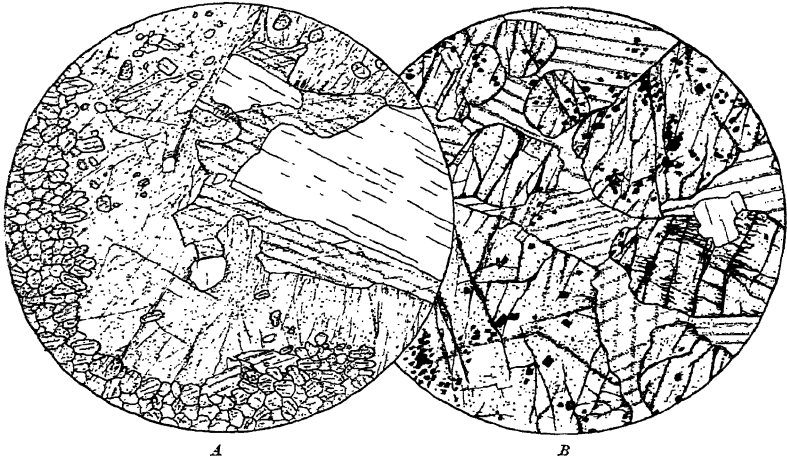


FIG. 51.—METAMORPHOSED AND PNEUMATOLYSED LIMESTONES, Grange Irish, near Carlingford, Co. Louth; $\times 23$.

A. This shows a concentric arrangement of the new minerals, consequent upon an original nodular structure. A large flake of phlogopite is surrounded by calcite, then by idocrase, and finally by diopside.

B. Monticellite-Calcite-rock, with little octahedra of nearly opaque (deep green) pleonaste and a few small flakes of phlogopite. Some *custertite* and phlogopite occur elsewhere in the slice.

fluorine is replaced by hydroxyl. The latter mineral, first known from American localities,¹ occurs locally in some abundance in the Carlingford district of Ireland.² Here it is associated with phlogopite, idocrase, monticellite, calcite, pleonaste, and apatite (Fig. 52). Probably the *custertite*, like the monticellite (Fig. 51, B), is a metastable form indicative of failure to reach equilibrium; and this is in accord with the varied diablastic intergrowths and poeciloblastic inclusions of the several minerals, pointing to a hasty crystallization of the whole.

¹ Umpleby, Schaller, and Larsen, *Amer. J. Sci.* (4), vol. xxxvi (1913), pp. 385-94; Tilley, *Geol. Mag.*, vol. lxxv (1928), pp. 371-2.

² Osborne, *Geol. Mag.*, vol. lxxix (1932), pp. 61-2, 219-20, 225-6.

The associations and relative proportions of the minerals vary greatly from point to point in the rock.

Fluorine enters exceptionally and in small amount into the composition of various common minerals of thermal metamorphism. Idocrase from Vesuvius contains about 1 per cent. and analyses of amphiboles of various kinds reveal traces of fluorine. Moreover, it is not impossible, even where no fluoride is now to be detected, that it may have played a part as a 'mineralizer', perhaps determining the formation of an amphibole rather than a pyroxene¹ or idocrase rather than grossularite.

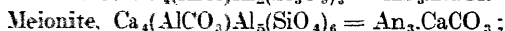
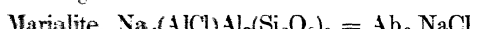


FIG. 52.—CUSTERITE-BEARING ROCKS, Grange Irish, near Carlingford, Co. Louth ; $\times 23$.

A. Idocrase-Phlogopite-Custerite-rock. The custerite is of xenoblastic habit, and sends out narrow strings between the idocrase crystals.

B. On the right are single large crystals of idocrase and phlogopite. The rest is an aggregate of custerite and calcite. Both phlogopite and custerite enclose very abundant little crystals of pleonaste.

The pneumatolytic action of *chlorides* is shown principally in the production of *scapolites* in limestones. The minerals of this group constitute an isomorphous series parallel with that of the plagioclase feldspars, and having as end-members :



while sulphate may also enter in the compounds $\text{Ab}_3.\text{Na}_2\text{SO}_4$ and $\text{An}_3.\text{CaSO}_4$.² The conversion of plagioclase to scapolite may often

¹ Von Eckermann, however, has described, from Mansjö in Sweden, a diopside containing 0.63 per cent. of fluorine: *Geol. För. Stock. Förh.*, vol. xlv (1922),

be observed in progress (Fig. 53, *A*); but other lime-aluminosilicates, such as idocrase and grossularite, may also be scapolitized, so that the process sometimes affects the chief bulk of the rock (Fig. 53, *B*). The chloride enters into actual combination with the albitic constituent of the felspar only, but by its influence as a 'mineralizing agent' the various lime-aluminosilicates become converted to meionite. The scapolities are idioblastic towards calcite and felspar, but xenoblastic towards the other lime-silicate minerals. Good illustrations of scapolitization are afforded by the Deeside limestone.¹

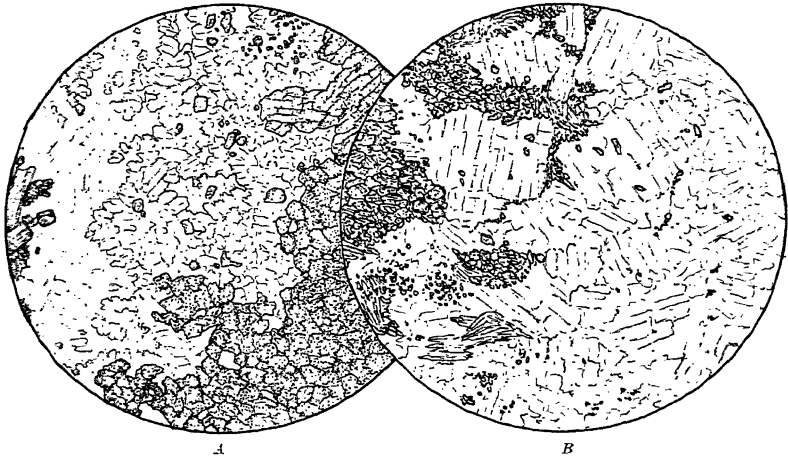
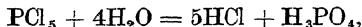


FIG. 53.—SCAPOLITIZED LIME-SILICATE-ROCKS, Etnich, near Deecastle, Aberdeenshire; $\times 23$.

A. Plagioclase felspar is seen on the left in process of replacement by scapolite, which occupies the centre of the field. The other minerals are grossularite and (above) idocrase.

B. Here scapolite fills most of the field, with diopside and some wollastonite. Elsewhere in the slice are grossularite, idocrase, and plagioclase.

A common associate of scapolite is *apatite*. In contradistinction to that which accompanies chondrodite and phlogopite, it is in the main a chlor-apatite. In both cases the mineral often occurs far too abundantly to be accounted for as part of the original substance of the rock, and we are led to the conclusion that there has been an introduction of *phosphate*, or rather of phosphorus in some volatile form. We may suppose this to react with water:



the acids so produced then entering into reaction with some of the silicates present.

¹ Hutchison, *Trans. Roy. Soc. Edin.*, vol. lvii (1933), pp. 581-2.

PNEUMATOLYSIS AND METASOMATISM

INTRODUCTION OF SULPHIDES AND OF IRON COMPOUNDS

Various *sulphide* minerals have a pneumatolytic or post-pneumatolytic origin. An interesting special case is that of lapis lazuli, which Brögger and Bäckström¹ have shown to be a metamorphosed dolomitic limestone. The blue lasurite, which is its distinctive mineral, is one of the sodalite group, which the authors regard as alkali-garnets, and they assign to it the formula $\text{Na}_4(\text{AlS}_3\text{Na})\text{Al}_2(\text{SiO}_4)_3$. Pyrites is one of the associated minerals.

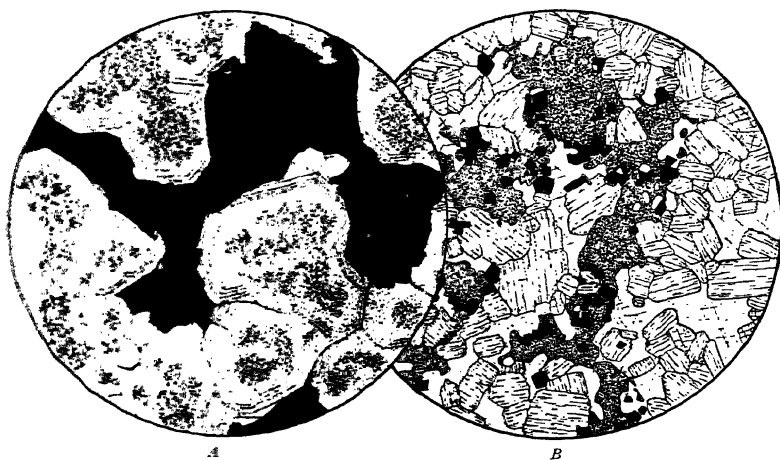


FIG. 54.—VARIETIES OF 'SKARN', FROM the Oslo district; $\times 25$.

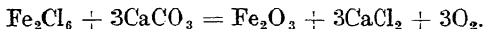
- A. Anurite-Magnetite-Skarn. Gjellebaek.
- B. Hedenbergite-Zinc-blende-Skarn. Nysaeter, near Grua. The opaque octahedra are of magnetite. Calcite and a little quartz occur interstitially. These and other types have been described by Goldschmidt.

More important are the ore-deposits found in some districts at the contact of limestones with granite and other plutonic rocks. These are the *skarn* of Scandinavian geologists and the 'garnet-contact-zones' of some American writers. Here sulphides of iron, zinc, lead, and copper, and in other occurrences magnetite, are associated with lime-silicates, chiefly garnet and pyroxene (Fig. 54). Kemp showed that the garnet is always of a variety rich in iron, containing up to 80 or 90 per cent. of the andradite molecule, and in like manner the pyroxene is near hedenbergite in composition. The iron in these silicates has clearly been derived from the igneous intrusion, which is equally the source of the ore-minerals. It is significant that these deposits are found in connexion with limestones, and that the ore-

¹ *Zeits. Kryst.*, vol. xviii (1890), pp. 231-75.

minerals have the appearance of replacing part of the substance of the limestone itself. The explanation of this is that an impure limestone suffers a very considerable diminution of volume when converted to an aggregate of garnet, pyroxene, wollastonite, epidote, etc. According to Barrell,¹ the shrinkage is as much as 30 or 40 per cent. of the volume. Allowing for the effect of pressure, it may still be believed that such a rock is sufficiently porous to give ready access to an invading fluid.

Whether the introduction of iron compounds into limestone rocks bordering a plutonic contact is truly a pneumatolytic process, is a question which has been debated. Goldschmidt² has suggested that the iron is introduced as a volatile chloride or fluoride, which reacts with calcite:



The chloride or fluoride would then go to make scapolite or fluor; minerals which are indeed found, but not generally or in abundance. Indeed it is clear from the descriptions of ores of this class in various countries that the presence of the ordinary pneumatolytic minerals is not usually a prominent feature. It is probable that the iron, etc., are introduced, not in gaseous form, but in liquid solutions at a somewhat later stage, and this is the view of most American geologists who have studied such occurrences.

The skarn type of metasomatism is found at numerous British localities, but usually as a narrow belt and with little of the impregnation with sulphides. Andradite-hedenbergite-rocks occur on the border of the Dartmoor granite³ (Fig. 55). At Tregullan, near Bodmin, too, lime-silicate rocks, carrying zinc-blende, contain a yellow garnet of andradite composition.⁴ In both cases borate minerals are also present (p. 120), and it is evident that the sequence of processes following the intrusion of the granite falls into three stages: (i) thermal metamorphism, (ii) pneumatolysis, (iii) invasion of iron-bearing solutions and introduction of sulphides. The occurrences described by Osborne⁵ in the Carlingford district are especially instructive. Here the thermal metamorphism proper is due to an intrusion of eucrite, but the iron-bearing solutions were derived from a subsequently intruded granite magma. The conversion of grossularite to andradite and of diopside to hedenbergite begins at numerous isolated spots in

¹ *Amer. J. Sci.* (4), vol. xiii (1902), pp. 279-96.

² *Vidensk. Skr.*, 1911, No. 1, p. 214.

³ Busz, *Neu. Jahrb. Min.*, Beil. Bd. xiii (1900), pp. 125-31, with analyses.

⁴ Barrow and Thomas, *Min. Mag.*, vol. xv (1908), p. 118.

⁵ *Geol. Mag.*, vol. lxxix (1932), pp. 226-7.

the metamorphosed rocks at some little distance from the igneous contact. At the actual contact these changes are complete: but the

tions have also reacted with residual calcite to produce the same lime-iron-silicates, and it is evident that there has been some accession of silica as well as of iron-oxides. Any wollastonite that may be present is left unchanged. Sulphides are represented only by a little pyrites.

ON OF SODA

Another type of metasomatism brought about by the agency of

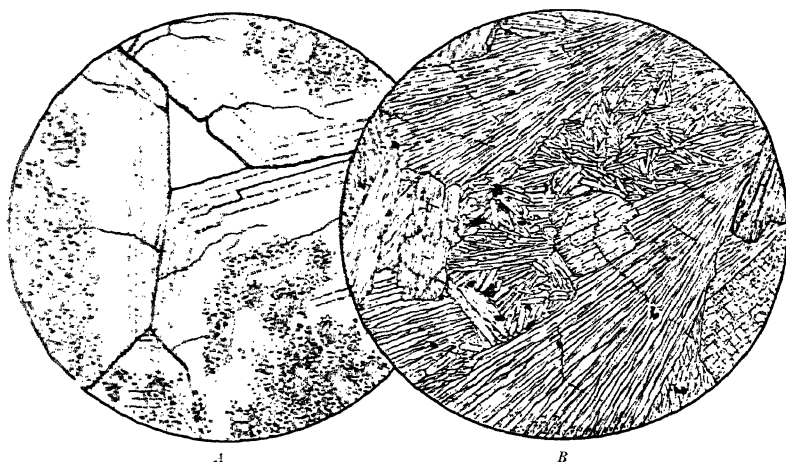


FIG. 55.—LIME-IRON-SILICATE ROCKS. Aish, near South Brent, in the aureole of the Dartmoor granite; $\times 23$.

A. Andradite-rock; composed mainly of large crystals of garnet, which in polarized light show rather strong birefringence and polysynthetic twinning. The marginal part of each crystal shows zonal growth, and the interior encloses crystals and grains of hedenbergite. The clear interstitial mineral is quartz.

B. Hedenbergite-rock, partly with a radiate grouping of slender prisms.

liquid solutions of magmatic origin is that which involves an accession of soda or of sodic compounds. A typical case is the albitization of the rocks bordering certain basic intrusions, whereby an argillaceous sediment is converted to an *adimole*. The igneous rocks responsible for this transformation are themselves rich in soda, and are generally interpreted as normal dolerites which, after their first consolidation, have been albitized by the action of 'juvenile' liquid carrying sodic compounds. The same liquid solutions have invaded the adjacent rocks for a few feet from the contact, not merely along fissures but by intimate permeation, and have there brought about metasomatic of a radical kind

The classical examples of adinoles are found in the Harz,¹ but comparable phenomena are known in many other districts.² The best British adinoles are in the Devonian slates of North Cornwall at their contact with sills of albite-dolerite³ (Fig. 56). The common type has the appearance of a chert, and in thin slices shows a very fine-grained texture; but there are coarser varieties, including one made up chiefly of spherulitic growths of albite crystals. The Cornish adinoles which have been analysed consist almost wholly of albite. Those of the Harz, although derived from similar slates, are albite-

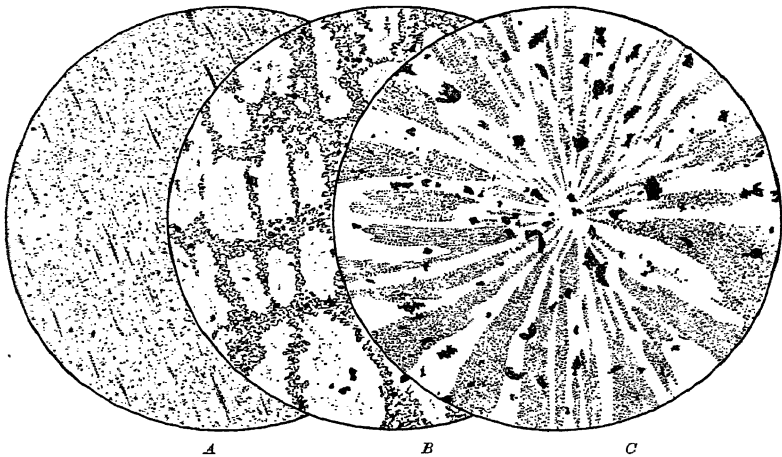


FIG. 56.—VARIETIES OF ADINOLE, from Dinas Head, near Padstow, Cornwall; $\times 25$.

A. Essentially a very fine-grained aggregate of albite: the original lamination of the slate is still indicated.

B. Containing a considerable amount of calcite in a network of veins. The albite here is in larger crystal-grains.

C. Showing a spherulite made by a radiate grouping of albite crystals. The opaque substance is white or yellow by reflected light, and is perhaps leucoxene: some chalybite is also present.

quartz-rocks with a variable proportion of other minerals, such as chlorite, epidote, actinolite, and iron-ore, sometimes with sphene or rutile. In a recent paper on the adinoles of Dinas Head in Cornwall, Agrell⁴ distinguishes four main types: (i) Normal adinoles—grading

¹ Kayser, *Zeits. Deuts. Geol. Ges.*, vol. xxii (1870), pp. 103-78; Milch, *ibid.*, vol. lxi (1917), pp. 349-486.

² An interesting occurrence in Michigan is described by Morgan Clements, *Amer. J. Sci.* (4), vol. vii (1899), pp. 81-91.

³ Howard Fox, *Geol. Mag.*, 1895, pp. 13-20; McMahon and Hutchings, *ibid.*, pp. 257-9.

⁴ *Min. Mag.*, vol. xxv (1939), pp. 305-36.

into rocks composed essentially of dravite (magnesian tourmaline). (ii) Adinoles with pseudomorphs probably after andalusite. (iii) Adinoles with globular masses of ankerite, showing concentric structures. (iv) Polygonal and spherulitic adinoles.

The adinole transformation, like ordinary thermal metamorphism, begins at isolated points within the rock. If it is arrested at an early stage, there results the peculiar type of spotted slate known as *spilosite*.¹ The spots may be seen to consist of albite, chlorite, and quartz, while the surrounding matrix is still mainly sericitic. In a more advanced stage the spots are composed essentially of granular albite, while the matrix is of quartz, albite, chlorite, actinolite, etc. Sometimes the change begins, not in distinct spots, but along selected seams of the sediment, giving a finely banded structure ('desmoisite').

The chemistry of the process presents a problem of some difficulty, but it is evident that a very radical replacement is implied. Besides addition of soda and silica, there has been a removal of magnesia, iron, and potash. Lime is probably removed also; but albitization may be followed by carbonization, likewise due to magmatic emanations, and calcite, ankerite, or chalybite is conspicuous in some adinoles. The replacement of substance must have been effected molecule by molecule, for the original lamination is not obliterated. The most essential change is the accession of soda, which may be regarded as taking the place of potash. The simple constitution of the Cornish adinoles suggests an introduction of albite *per se*, while in the Harz a variable amount of silica has also been added. That albite may be introduced bodily into a rock seems to be indicated by its manner of occurrence in certain limestones.² A good example has been described by Lacroix³ in the Pyrenees. The crystals show a variety of habit unlike anything seen in thermal metamorphism. They are associated with phlogopite, chlorite (leuchtenbergite), pyrites, quartz, and sphene (Fig. 57. A). The type of metasomatism of which adinole represents the extreme product, viz. an accession of soda which, now at least, is contained in albite, is a widespread effect at the contact of argillaceous rocks with dolerite sills. It is well shown near the Whin Sill in Teesdale,⁴ and about Tremadoc and elsewhere in North Wales.⁵ It is to be suspected whenever chemical analysis shows a marked preponde-

writers have applied this name more generally to spotted slates, without reference to albitization.

¹ Spencer, *Min. Mag.*, vol. xx (1925), pp. 365-81 (Bengal).

² *Bull. Carte Géol. Fra.*, vol. vi, No. 42 (1895), pp. 85-6.

³ *Ann. Mag. Nat. Hist.*, 1895, pp. 122-31, 163-9.

British Petrography (1888), pp. 217-21.

rance of soda over potash. Not only basic, but sometimes acid igneous rocks, themselves rich in soda, may be attended by like effects. Goldschmidt has noted several instances at the contacts of nordmarkites and soda-granites in the Christiania district.

Metasomatism by the agency of soda-bearing solutions has also been invoked to account for the production of *paragonite*. Such is the contention of Killig ¹ in the case of the Ochsenkopf in the Saxon Granulitgebirge, but the evidence adduced is not wholly convincing. Here again the action premised is of a very drastic kind, not merely

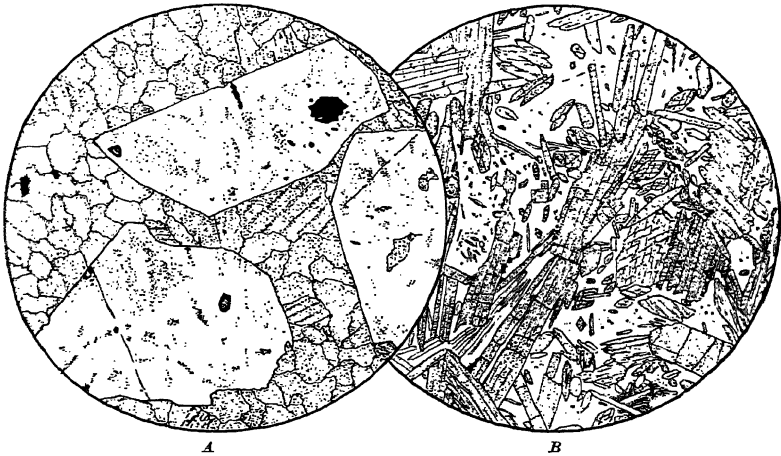


FIG. 57.—ALBITIZED ROCKS; $\times 25$.

A. Albite crystals in metamorphosed Jurassic limestone near contact with lherzolite, Roc Tourné, Modane, Hautes Pyrénées.

B. Quartz-Glaucophane-schist, Ollard, New Caledonia. Crystals of glaucophane, large and small, are embedded in a mosaic of albite and quartz.

potash-mica but a phyllite as a whole being converted to *paragonite*. Connected apparently with the same process, there has been also an introduction of sulphide-ores.

In some cases there has been an introduction of ferric iron, as well as of soda and silica. Thus, in the sericite-phyllites of Winterburg in the Hunsrück ² there has been an abundant production of a soda-amphibole (crossite). There are indications that this preceded the injection with albite. An introduction of soda-bearing amphiboles, and more rarely pyroxenes, is found also in some metamorphosed arenaceous rocks. Goldschmidt ³ has observed this effect in a lenticle

¹ *Mitt. Nat. Ver. Greifswald*, 1912.

² Chudoba and Obenauer, *Neu. Jb. Min.*, Beil. Bd. lxiii, A (1931), pp. 77-80.

³ *Neu. Jb. Min.*, Beil. Bd. xxxix (1914), pp.

of sandstone enclosed in a pegmatite dyke in the Langesundsfjord. The percentage of soda has been raised from 0.89 to 3.47, and ferric oxide has probably been added also. More remarkable are the *quartz-glaucophane-schists*. Washington¹ has pointed out that glaucophane-schists in general fall into two main groups. Those of basic composition represent igneous rocks modified by regional metamorphism. The rarer type with a high silica-percentage (75 to 80 or more) comes from metasomatic transformation of siliceous sediments. In California not only sandstones but radiolarian cherts are proved to have

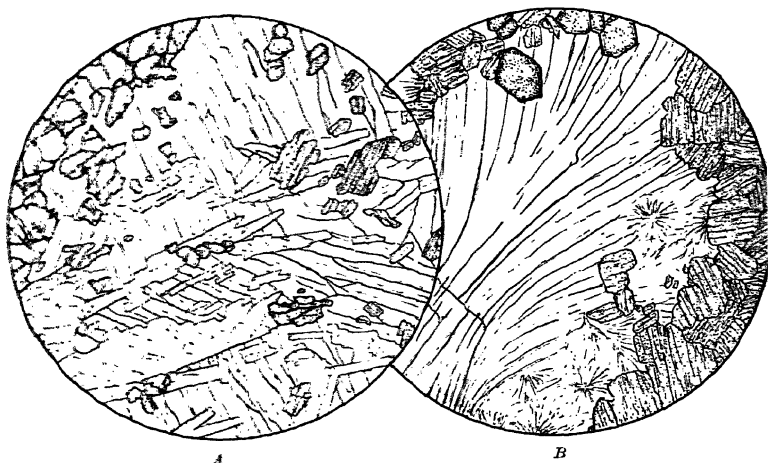


FIG. 58.— LIME-SILICATE ROCKS, Pollagach Burn, near Cambus o' May, Aberdeenshire; $\times 23$.

- A. The coarsely crystalline prehnite, making more than half of the rock, comes in the main from lime-felspar and perhaps idocrase, but grossularite is also being attacked. Diopside remains untouched, but wollastonite is represented by pseudomorphs in calcite.
- B. This shows the common tendency of prehnite to sheaf-like and radiate-fibrous crystallization. The other minerals are diopside and a few dodecahedra of grossularite.

suffered this change. The rocks consist essentially of quartz and glaucophane with or without albite, and the percentage of soda may range as high as 6 (Fig. 57 B).

OTHER METASOMATIC CHANGES

Here should perhaps be included certain metasomatic transformations in which heated water, of magmatic origin, seems to have the sole agent, or is at least the only one which has left direct evidence. Among processes which may be attributed primarily to this hydrolytic

action is the *prehnitization*¹ of various lime-aluminosilicates. In some localities, always in the near neighbourhood of a plutonic contact, this destructive action has been carried far, even in the extreme case to the reduction of the whole rock to an aggregate essentially of prehnite and quartz. Any lime-felspar present is first converted. Anorthite, however, has a lower ratio $\text{CaO} : \text{Al}_2\text{O}_3$ than prehnite, and accordingly, unless calcite be present, the more calcic minerals are attacked in their turn, viz. idocrase and then grossularite. The non-aluminous silicates, diopside and wollastonite, are exempt, but there may be a simultaneous replacement of wollastonite by calcite (Fig. 58).

It is well known that some geologists attribute far-reaching consequences to the agency of magmatic solutions as introducing, not only silica, soda, and iron-compounds, but alumina, magnesia and potash. The French school, and Lacroix in particular, have attached great importance to this metasomatic element as applicable to metamorphism on an extensive scale. It has also been invoked as an important factor by Adams and Barlow in Canada.² This is not the place to discuss a question which turns largely upon the interpretation of field-evidence, but one general consideration may be recalled. The normal course of crystallization in a cooling igneous rock-magma is now sufficiently well understood in its main lines. It enables us to account for the concentration in the final residual magma, in different cases, of soda or silica or iron compounds, as well as an enrichment in water and other volatile bodies. Magnesia, on the other hand, is selectively taken out in the earlier stages of crystallization to make olivine and pyroxenes and, it may be, later for amphibole and biotite (perhaps at the expense of the former minerals), with the result that the residual magma in the final stage is normally devoid of magnesia. This is not to be forgotten when magnesian solutions, of magmatic origin, are invoked to explain dolomitization or to account for the production of abundant biotite and hornblende in a supposed pure limestone.

Perhaps the strongest case for recognizing metasomatic changes of this kind is the abundant production of such magnesian minerals as cordierite and anthophyllite in some aureoles of metamorphism. A standard instance is that described by Eskola³ in the Orijärvi

¹ Compare Hutchison, *Trans. Roy. Soc. Edin.*, vol. lvii (1933), pp. 575, 583-6 (Deeside Limestone).

² *Geology of the Haliburton and Bancroft Areas (Mem. No. 6, Geol. Sur. 1910).*

³ *Bull. No. 49, Com. Géol. Finl. (1914), pp.*

district of Southern Finland. Here anthophyllite-cordierite-rocks and allied types have been produced in the 'leptite' formation bordering an intrusion of oligoclase-granite. There is evidence of the replacement of lime and alkalis by iron-oxides and magnesia, and this is attributed to the action of emanations from the granite-magma.

It must be recognized, however, that, in other occurrences, drastic changes of bulk-composition have been brought about in the near vicinity of a plutonic intrusion by the agency of heated water alone. An instructive example is that of certain greatly altered dolerites near

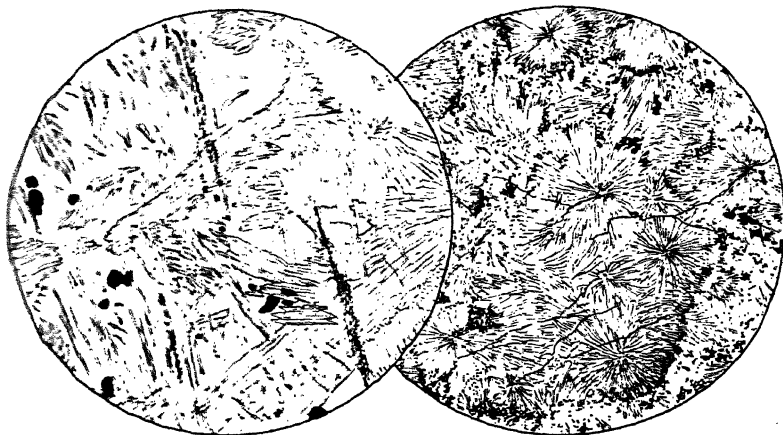


FIG. 59.—ANTHOPHYLLITE-CORDIERITE-ROCKS, Kenidjack, Cape Cornwall; $\times 23$.

A. Columnar crystals and slender needles of anthophyllite are embedded in a mosaic of cordierite. The only other constituents are a few crystals of pleonaste and magnetite and thin plates of ilmenite preserving their original position.

B. Here the anthophyllite has the radiate-fibrous habit. Magnetite is rather t. especially interposed between anthophyllite and cordierite.

the Land's End granite of Cornwall.¹ These, prior to metamorphism, had suffered shearing, and the metamorphosed rocks show in consequence a banded structure, with much variety in the different bands. The simplest type consists essentially of a green aluminous hornblende with plagioclase. In other associated rocks, however, hornblende gives place to one of the non-calcic amphiboles, cummingtonite and anthophyllite, and plagioclase is represented by cordierite, a characteristic type being an *anthophyllite-cordierite-rock* (Fig. 59). Other significant minerals which may enter are pleonaste and diaspore. Ilmenite and apatite occur as residual elements.

and Flett, *Sum. of Progr. Geol. Sur.* for 1929, Part II (1930), pp. 24-41; Tilley, *Min. Mag.*, vol. xxiv (1935), pp. 181-202.

The loss of lime, which is here the most evident chemical change, might conceivably be due to weathering of the dolerite, and this would automatically raise the proportion of alumina, magnesia, etc. Tilley has, however, made it clear that the more remarkable of these metamorphosed rocks have no equivalent among known products of atmospheric weathering. Analyses indicate, in different cases, in addition to and compensating the abstraction of lime, an accession of silica, iron-oxides, magnesia, and potash. These substances, nevertheless, were all contained in the original dolerite, and only the redistribution of them is ascribed to the agency of heated water from the granite magma.

PART II

DYNAMIC AND REGIONAL METAMORPHISM

CHAPTER X

STRESS AS A FACTOR IN METAMORPHISM

Analysis of Strain and Stress—Influence of Stress on Solubility—Influence of Stress on Chemical Reactions—Stress- and Anti-stress Minerals.

ANALYSIS OF STRAIN AND STRESS

WHEN rocks suffer metamorphism in response to rise of temperature under the relatively simple mechanical conditions hitherto assumed—viz. under no external force other than hydrostatic pressure—there is no deformation of the rock-masses affected. There may be a uniform compression, but, except in certain special cases (p. 127), the actual diminution of volume is not important. The internal stress experienced under such conditions is primarily a mere uniform pressure. It is true that in theory some shearing stresses must always be set up in addition, both by the compression of a heterogeneous mass (p. 6) and as a consequence of crystal-growth (p. 33); but such stresses are in great measure automatically relieved by the co-operation of causes already indicated.

In metamorphism of the most general kind, with which we are now concerned, these factors making for simplicity are no longer present. Rock-masses, at some lower or higher temperature, are subjected to external forces which are different in different directions, e.g. to a lateral thrust. They yield in greater or less degree according to the magnitude of the forces and the resistance of the rocks (at the given temperature). In so far as they yield, they suffer deformation. In so far as they resist, internal shearing stresses are set up; and these stresses, being maintained or renewed so long as the external forces are operative, attain a magnitude far beyond anything that is possible in simple thermal metamorphism. The hydrostatic pressure may be very high at the same time, but is not necessarily so.

Since we meet here with conceptions, both geometrical and

mechanical, not hitherto encountered, it will be convenient to begin by recalling briefly some of the principles involved.

Ideally, deformation of a solid body may be continuous or discontinuous, the latter term implying finite slipping of one part against another, i.e. internal faulting on a small scale. The distinction which we shall actually make is indeed one of degree rather than of kind; for *strictly* continuous deformation, such as is shown by india-rubber, is scarcely possible in a rock composed of discrete elements. Deformation of a plastic clay is, however, continuous to the eye, and we shall see that concurrent physical and chemical changes may confer a measure of effective plasticity even on a crystalline rock. We shall accordingly begin with a simplified discussion of deformation, or in mathematical phrase *strain*, of a continuous or quasi-continuous kind. The external forces which set up the strain and the internal stresses thereby called into play are not at present in question, the treatment being purely geometrical.¹

In a large body strain is not necessarily uniform throughout; but it is sensibly so for any small part of such body, and we shall confine our attention to this case. In general a strained body suffers both change of volume and change of shape, and these can be considered separately. There are accordingly two fundamental types of strain: (i) a uniform contraction or elongation in all directions (change of volume only) and (ii) a simple shear (change of shape only). The former needs no description. It may be a purely mechanical effect or an incident of chemical reactions in the rock. The diminution of volume is small, except where there is actual loss of material, as in the squeezing of water out of a clay or the expulsion of carbon dioxide in the metamorphism of an impure limestone.

The simple *shear*² calls for a more particular consideration. It is most easily pictured as the type of strain by which the cube of Fig. 60 is deformed into the oblique parallelepiped of Fig. 61. Here each horizontal plane in the body, without suffering distortion, is displaced, relatively to the base, in the direction DC through a distance proportional to its height above the base. The ratio $DD' : AD$, or $\tan \theta$, measures the 'amount of shear'. The character of any strain is, however, most completely and conveniently expressed in terms of the 'strain-ellipsoid', i.e. the figure into which a sphere in the unstrained

¹ For a full analysis of strains and the correlated stresses see Thomson and Tait's *Natural Philosophy* or other work of reference.

² The term is here used in the mathematician's sense. As such it was introduced into geological literature by Fisher, but it has since come to be more employed, so as to include deformation which is essentially discontinuous.

body becomes deformed. Let r be the radius of the sphere and a, b, c , the greatest, mean, and least semiaxes of the ellipsoid, a and c lying in the plane of the figure and b perpendicular to it. Then every line in the body parallel to a has been elongated in the ratio $a : r$, and every line parallel to c has suffered a corresponding contraction. The ratio $a : r = r : c = s$ is called the 'ratio of the shear', and the amount of shear is connected with this by the relation $\tan \theta = s - 1$.

Since all particles in the body are displaced in planes parallel to that of the figure (called 'planes of shearing'), any line perpendicular

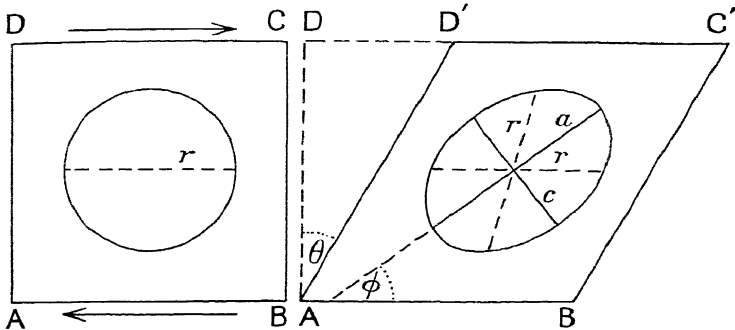


FIG. 60.—SECTION THROUGH A CUBE, PARALLEL TO ONE PAIR OF FACES.

FIG. 61.—THE SAME DEFORMED BY UNIFORM SHEAR PARALLEL TO THE BASE.

to these planes is unchanged in length, and the mean semiaxis $b = r$. The relation $ac = r^2$ or $abc = r^3$ expresses the fact that there is no change of volume.

The greatest axis is inclined to AB at an angle ϕ , such that $\cot \phi = s$. Now an ellipsoid with three unequal axes has two sets of plane circular sections, parallel to the mean axis and symmetrically inclined to the other two. One set is evidently given by horizontal planes, which are 'planes of no distortion', and the other set must be equally inclined to a on the opposite side. Consider first a shear of infinitesimal amount: then s differs only infinitesimally from unity, and $\phi = 45^\circ$. It follows that everything is symmetrical about the diagonal AC ; the second set of circular sections is vertical; and it is indifferent whether the infinitesimal displacement was made parallel to AB or to AD . In either case the effect of the shear is equivalent to a certain elongation parallel to the diagonal AC with a compensating contraction parallel to BD . If now we suppose shearing to continue, so as to bring about deformation to any finite extent, it is evident that this may be con-

ducted upon more than one plan. We may distinguish two cases, both of which have their application to the deformation of rock-masses:

(i) First suppose AB held in a fixed position—say horizontal—and DC dragged continually to the right. As this goes on, the strain-ellipsoid is continually becoming more elongated and narrowed, and its greatest axis is rotated towards the horizontal; i.e. s increases and the angle δ continually diminishes.

(ii) Next suppose instead that the axes of the strain-ellipsoid are fixed in direction—say with the greatest axis vertical (Fig. 62). We

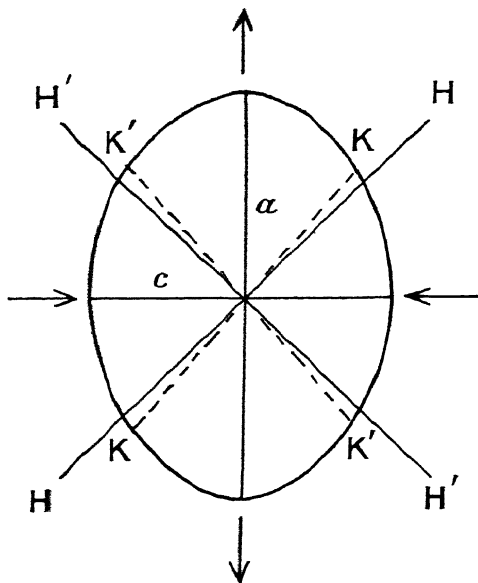


FIG. 62.—DIAGRAM TO ILLUSTRATE CONTINUED SHEARING BY LATERAL CONTRACTION AND VERTICAL ELONGATION

have seen that an infinitesimal elongation in the direction of a with a compensating contraction in the direction of c is equivalent to a certain shear, the planes of no distortion being those parallel to HH and HH' , making angles of 45° with the axes of the ellipsoid. Evidently continued elongation and contraction on the same lines will be equivalent to continued shearing. Planes parallel to HH and $H'H'$, fixed in space but not fixed with reference to the body undergoing

are at every stage planes of no instantaneous distortion, the circular sections, parallel to KK and $K'K'$, are planes of no distortion.